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PRELIMINARY CONCEPT, SPECIFICATIONS, AND REQUIREMENTS FOR A ZERO-GRAVITY COMBUSTION FACILITY FOR SPACELAB

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SUMMARY

This document describes the preliminary concept, specifications, and requirements of a reusable zero-gravity combustion facility (0-GCF) for use by experimenters aboard the Spacelab payload of the Space Transportation System (STS) Orbiter. The facility will be amenable to any mission of the STS Orbiter in which a Spacelab habitable segment and a pallet segment are integral and for which orbital mission plans specify induced accelerations of 10^{-4} g or less for sufficiently long periods so as not to impact experiment performance. With the proposed facility a wide variety of combustion research experiments can be performed from rapid burning to long-term smoldering.

The design permits an experimenter (1) to use suitably contained liquid, gaseous, or solid fuels, (2) to specify and establish the composition and pressure level of the atmosphere in which the combustion will take place, (3) to characterize the experiment with common types of instrumentation as well as selected specialized equipment, and (4) to study the combustion process visually by direct observation and by motion-picture coverage and to obtain time histories of pertinent experimental parameters.

Although the facility will supply its own expendables (e.g., fuels, oxygen, and inert gases), it will depend on the Spacelab and Orbiter resources for power, heat rejection, data management, communications, and the services of a payload specialist as the test conductor.

For Spacelab missions with the proposed facility, the scientists and their experiments will probably be selected through an Announcement of Opportunity issued by NASA. Hence, use of the 0-GCF will be open to the entire scientific community.

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INTRODUCTION

In-house and contracted research into the effects of gravity on various combustion processes has been conducted within the NASA program for many years. The information from these studies is being used to design fire-safety features for space vehicles. It is also being used extensively in basic research to assess the effect of gravity on the fluid dynamics and heat-transfer characteristics of various combustion processes and to construct more accurate combustion models by using data taken on a fundamentally simpler system (i.e., a combustion experiment without the influence of gravity).

There are, however, some major restrictions to ground-, aircraft-, and rocket-based "zero gravity" combustion experimentation. Two such restrictions are the length of test time available and the preclusion of direct participa-

tion by the principal investigator or scientist in the experiment. The advent of the Space Transportation System (STS) Orbiter and its Spacelab payload will, to a large degree, eliminate these restrictions.

The NASA Lewis Research Center sees the Orbiter/Spacelab combination as a significant tool to further the ongoing basic research in combustion phenomena Consequently an overview study was sponsored by the Lewis Research Center in 1974 to determine those combustion areas with a strong scientific basis for continued research in the low gravity offered by orbital missions. Among the results of this study was the conclusion that a combustion research program, as opposed to a few isolated experiments, should be seriously considered Hence, instead of thinking only in terms of individual experiment hardware, we devised the concept of a reusable facility within Spacelab. The results of the 1974 study were used to select six specific experiments, in widely differing areas of combustion research as a baseline for a facility design. The selected experiments include studies of gas-mixture flammability limits, particle-cloud combustion, liquid-pool burning, droplet burning, single-solid-particle combustion, and smoldering These experiments were not considered as constituting the limits of the proposed facility, but only as typical examples of the experimental work which should be conductable.

This document describes the preliminary concept, specifications, and requirements of a proposed zero-gravity combustion facility (0-GCF) for Spacelab. Included are the overall philosophy behind the design, the basic facility design, and the author's concept of the overall operational sequence of the facility. The majority of the report is a description of the hardware required as well as the concepts for implementing it in the facility This description is not pure specification nor is it pure design - rather it is a combination of both that together form the basic thinking from which the author believes will evolve the finalized design of a combustion facility.

The proposed Spacelab zero-gravity combustion facility will be a multipurpose facility for performing combustion research in a very low gravitational field It will allow a wide variety of combustion experiments, from rapid burning to long-term smoldering, to be performed in a low-gravity environment.

The 0-GCF, which is presently conceived as a partial payload of the Spacelab, will be carried into Earth orbit and returned to Earth on selected Space Transportation System Orbiter flights The facility will be amenable to any mission of the STS Orbiter in which a Spacelab habitable segment and a pallet segment are integral and for which orbital mission plans specify induced accelerations of 10^{-4} g or less for sufficiently long periods so as not to impact experiment performance.

All assembly, installation, refurbishment, and major maintenance and repair operations on the facility will be performed on the ground. The facility will be passive during prelaunch ground operations, as well as during the launch, ascent, and descent phases of the flight.

Facility operations will begin after orbit has been achieved. At this time the facility will depend on the Spacelab resources for power, heat rejection, vacuum, and data management and communications. A payload specialist will be required to activate the facility, to prepare it for various experiments, to perform the experiments, to ascertain that adequate data have been obtained and properly stored or transmitted, to deactivate the facility, and to secure all experimental as well as some facility equipment for return to Earth before starting descent. Upon completion of the mission, the Spacelab will be removed from the Orbiter and will be made available for the removal of the 0-GCF and its maintenance and refurbishment in preparation for another flight.

For Spacelab missions with the proposed combustion facility, the principal investigators and their experiments will most probably be selected through an Announcement of Opportunity issued by NASA. Hence, use of the proposed facility will be open to the entire scientific community.

DESIGN PHILOSOPHY

The purpose of the proposed Spacelab zero-gravity combustion facility is to permit a wide variety of combustion research experiments, from rapid burning to long-term smoldering, to be performed in a low-gravity environment (10^{-3} to 10^{-5} Earth g). The 0-GCF is being designed as a versatile, reusable research facility that will enable the experimenter to make optimum use of the shirt-sleeve Spacelab environment to study combustion processes free of the buoyancy forces of Earth-bound laboratories.

The 0-GCF will permit the experimenter (1) to use suitably contained liquid, gaseous, or solid fuels, (2) to specify and establish the composition and pressure level of the atmosphere in which the combustion takes place, (3) to characterize the experiment with common types of instrumentation as well as selected specialized equipment, and (4) to study the combustion process visually by direct observation and by motion-picture coverage and to obtain time histories of pertinent experimental parameters.

BASIC DESIGN

The zero-gravity combustion facility, as conceptualized, has the following major elements:

(1) Combustion chamber

(2) Gas and liquid supply systems and bottle storage area

(3) Combustion-chamber vent assembly

(4) Combustion-chamber console, subsystems, and satellite hardware

(5) Data acquisition and control subsystems

The combustion chamber will be installed in a Spacelab modified double-rack console and will use standard Spacelab mechanical and electrical interfaces. Fluid and gas resources will be furnished by the facility and will be stored outside the habitable volume of Spacelab Vented liquids, gases, and products of combustion will be dumped outboard of the Orbiter structure. A center-aisle cabinet will be used for storage of experimental equipment and supplies. The facility will incorporate certain housekeeping specifications to maintain cleanliness of the combustion-chamber volume. The facility design will be capable of withstanding the ground and flight environments anticipated.

Figure 1 is an artist's concept of the 0-GCF. Figure 2 shows a preliminary mockup of the Spacelab console. Figure 3 is a schematic of the major plumbing of the facility. These figures are not meant to show mounting preferences but are presented as an aid in visualizing the major hardware elements of the facility.

FACILITY FUNCTIONAL DESCRIPTION

All experimental apparatus to be used inside the combustion chamber will be stowed within the habitable volume of Spacelab during the prelaunch, launch, and orbit-establishment phases of the flight. Facility operations will begin sometime after orbit has been achieved.

The payload specialist will determine that a breathable atmosphere exists within the chamber and that the pressure in the chamber is equalized with that in Spacelab. He will remove the service ports in the chamber and manually mount one set of experimental apparatus inside the chamber. The payload specialist will then make the mechanical, pneumatic, hydraulic, and electrical connections between the experimental apparatus and the chamber. He will reseal and evacuate the chamber preparatory to later loading of fuel samples and establishment of the desired combustion atmosphere within the chamber. After he vacuum purges the plumbing transfer lines, the payload specialist will open the valving that isolates the line volumes from the storage tanks outside the

Spacelab habitable volume to charge the lines with the gases and/or liquids needed for the experiment.

Experiments that use gases in closable experiment-furnished volumes can be loaded by remote control while a vacuum exists within the chamber. The chamber will then be pressurized with the atmosphere desired for the combustion process. For some other experiments, the desired atmosphere for combustion will be established before remote loading of the fuel sample. Other experiments will require an ordinary air atmosphere in the chamber to allow manual loading of the fuel sample. Loading of these samples will be followed by a second vacuum purge before finally establishing the desired atmosphere composition and pressure level required for combustion. Upon completion of the chamber-loading phase, the payload specialist will activate the data-recording instrumentation, and the combustion process will run to the desired degree of completeness. After the experimental run the chamber will be evacuated to space and repressurized with facility-generated air.

The facility will be shut down by first isolating all remaining gas and liquid supplies within their storage tanks. After the chamber and the fluid transfer lines are vacuum purged, the chamber will be repressurized, the experimental apparatus will be removed and stowed, and the electrical equipment will be deactivated.

Upon completion of the mission, the Spacelab will be removed from the Orbiter and will be made available for the removal of the 0-GCF and its maintenance and refurbishment in preparation for another flight.

REQUIREMENTS AND CONCEPT OF IMPLEMENTATION OF FACILITY HARDWARE

The NASA Lewis Research Center sponsored an overview study in 1974 to determine those combustion areas with a strong scientific basis for further research in zero gravity. From the results of that study, six experiments, in widely differing areas of combustion research, were selected to form a baseline for the design of a test facility. The proposer of each experiment was required to provide, as a definition study, (1) a formal justification (analytical and experimental) of the experiment, (2) a feasibility study defining key methods of conducting these tests, and (3) a formal conceptual design of the experiment. During the definition studies, and in conjunction with the proposers of the experiments, this author used key design details from the experiments to develop specifications for a combustion facility.

The overall and specific physical characteristic requirements for the 0-GCF presented herein characterize the facility and form the basis for its technical features and future development. Also specified are the different environments to which the 0-GCF will be exposed.

Combustion Facility Chamber

Basic geometry of chamber. - The combustion chamber will be a cylinder 0.61 meter (24 in.) in outside diameter by 1.2 meters (47 in.) long with 1:4 elliptical head ends. The overall height of the chamber will be approximately 1.5 meters (59 in.), the maximum height available for experimental hardware in the console. These dimensions will permit the chamber volume to be used as an enclosed plenum during five of the six baseline experiments for facility design.

Material of construction. - The material will be stainless steel.

Internal volume. - The internal volume of the chamber will be as large as permitted by structural and volume considerations of all feedthroughs, gas distribution hardware, and operating pressure requirements.

Working pressure. - The range of chamber working pressure will be $\pm 10.1\ N/cm^2$ gage (± 14.7 psig).

Safety factor. - The safety factor will be at least 2, relative to the yield strength of the material, and will be based on a buckling or compressive load of $10.3\ N/cm^2$ differential (15 psid).

Allowable heat release within chamber. - The heat release will be limited to 342 watt-hours (100 Btu) per experimental run. This is the minimum quantity of heat that will adiabatically raise the air pressure in the enclosed chamber from 1 atmosphere to 2 atmospheres.

Optical-quality ports. - A minimum of four ports will be located on the "sides" of the cylindrical combustion chamber. Their 10.2-centimeter- (4-in.-) diameter usable openings will have coverplates of optical-quality transparent material (i.e., $\geq 0.8\ \tau$ in the visible spectrum, where τ denotes transmissivity). The transparent material used will result in no aberration or diffusion of transmitted light. Three ports will be alined on one side of the chamber, with their vertical axes parallel to the vertical axis of the chamber. The horizontal axes of these ports will be 56, 81, and 104 centimeters (22, 32, and 41 in.), respectively, above the horizontal plane of the chamber bottom-dead-center. The upper and lower ports will be used for motion-picture coverage of combustion experiments within the chamber. The middle port will be used as the entrance port for a helium-neon laser beam directed

at experimental hardware located coaxially with the chamber vertical axis. A fourth optical port will be diametrically opposite to (i.e., across the chamber diameter from) the middle port of the three previously mentioned ports. This port will allow a photocell (mounted outside the chamber) to observe the experiment being irradiated by the laser beam All four ports are meant to be removable only during major ground servicing of the 0-GCF.

Service ports. - As presently envisioned, there will be three elliptical service ports on the "front" of the cylindrical combustion chamber. The major and minor axes of each service port will be 25.4 and 15.2 centimeters (10 and 6 in.), respectively. When not covered these ports will be unencumbered by any other protrusions or chamber subcomponents. The major axes of the two uppermost ports will be parallel to the vertical axis of the chamber. The major axis of the lower port will be normal to the vertical axis of the chamber. The horizontal axes of the three ports will be 28, 69, and 119 centimeters (11, 27, and 47 in.), respectively, above the horizontal plane of the chamber bottom-dead-center. Each service port will have a coverplate of optical-quality transparent material (i.e., $\geq 0.8\ \tau$ in the visible spectrum). The area of the transparent material will be the same as the opening in the chamber. Further, each coverplate must be easily removable (to allow access to the chamber interior) and easily resealable (to reisolate the chamber volume) during in-flight testing periods. Seals must be easily refurbished or replaced during ground servicing of the 0-GCF.

Gas distribution hardware. - Nitrogen, cabin air, and perhaps Halon must be put into the chamber in a manner that insures precise volumetric distribution and also promotes forced convective mixing with other gases already in the chamber. The distribution hardware will accommodate the anticipated inflow conditions for these particular service gases (rates specified elsewhere). Only a small pressure budget will be needed to distribute and mix the incoming gas.

Exhaust-gas filter screen. - All gases leaving the combustion test volume will be forced to flow through a screened "sieve" in the upper elliptical head end of the chamber. This sieve will serve as a hard-mounted, cleanable filter for particulate matter ($\geq 100\ \mu m$ in diam) generated during the combustion experiments. The filter material will serve only as a mechanical trap for the undesirable particles and will release them to a vacuum-operated cleaning tool. The vacuum tool, which will be hand held by a payload specialist, will be inserted through a service port in the front of the chamber. Finally, a filter screen design that requires only a small pressure budget during chamber venting operations will be used.

Interior chamber illumination for experiment servicing. - The chamber interior must be lighted during periods of experimental hardware assembly, servicing, and disassembly. Light from the Spacelab cabin entering through the service and optical ports of the chamber will not be, in itself, sufficient for the work envisioned. A minimum of two ports, with 10.2-centimeter- (4-in.-) usable openings covered with optical-quality transparent material, will be required in addition to the optical and service ports. These additional ports will be positioned in the cylindrical centerbody section of the chamber near the elliptical head ends. Outboard of each specified port (but still within the volume of the console) will be a housing containing a light source approximately equal to a 40-watt fluorescent light bulb. These light sources will be jointly controlled from a single switch on the console control panel. There will be no communication, other than optical, between the combustion chamber and the housing containing each light source. The port covers are meant to be removable, and the light sources replaceable, only during major ground servicing of the 0-GCF.

Interior chamber illumination for "backlighting" of experiments. - At least one of the presently proposed experiments will require backlighting illumination during the testing period. One lighting port should satisfy the requirement. As a result, one extra lighting port and bulb housing assembly will be included in the chamber design. This port in the chamber wall will be diametrically opposite to the lower camera optical port. This light will be controlled either by a switch from the console front panel or automatically actuated as part of a programmed, time-lined, experimental sequence.

Hose connections on interior wall of chamber. - The proposed experiments require the transfer of experimental gases and/or liquids from their supply tubing penetrations at the chamber wall to experimental hardware apparatus specified by the participating principal investigators. It is presently envisioned that this transfer will take place through flexible tubing manually installed by the payload specialist for each specific experiment and that it will be controlled by valving outside the combustion chamber (see the section Gas and Liquid Supply Services and Bottle Storage). Because hard-mounted hose connections will be used on the interior chamber wall, the payload specialist will be able to establish, and quickly break down, reliable leak-free joints during experimental hardware assembly and disassembly.

Electrical feedthroughs. - Individual experiments within the chamber will use measurement transducers that are basically of a thermoelectrical, mechanoelectrical, or optoelectrical nature. In addition, some experiments will also

use fractional electric motors as well as electrical ignition devices. Electrical continuity from these devices will be furnished through the chamber wall by means of a series of electrical bulkhead fittings mounted on a removable service panel. This removable panel, which will be part of the chamber wall, will contain a minimum of five 3-centimeter- ($1\frac{1}{4}$ -in.-) diameter bulkhead feedthroughs. The number and type of pins in each fitting are to be determined. Further, this service panel must be easily removable (for ease in connecting wiring harnesses from the experimental apparatus to the inboard side of the fittings) and easily resealable (to resecure the chamber volume) during in-flight testing periods. All fittings, as well as any seals used, must be easily refurbished or replaced during ground servicing of the 0-GCF.

The service panel will be located so that the exterior (or outboard) ends of the bulkhead fittings are easily accessible to a payload specialist standing in front of the combustion chamber. He can thus easily connect wiring harnesses from the combustion chamber to a "patchboard interchange" (see the section Facility Console, Subsystems, and Satellite Hardware) on the console. This arrangement should allow electrical connections to be made to an experiment within the combustion chamber by means of prefabricated wiring harnesses made specifically for that experiment.

Chamber-atmosphere recirculation system. - In all likelihood, combustion-generated particulate matter will not be completely removed from the chamber volume solely by venting to space. For further cleansing of the chamber volume, while still conserving facility gas resources, a chamber-atmosphere recirculation system will be incorporated into the facility. The system will be used as necessary, but only when there are no active experiments in the chamber. This closed-loop system, which will also contain its own filter external to the chamber, will recirculate the chamber atmosphere by withdrawing gas downstream of the exhaust-gas filter screen and reinjecting it back into the main volume of the chamber. By so doing, a continuous gas flow can be maintained. The exhaust-gas filter screen will entrap particulate matter 100 micrometers, or greater, in diameter; the filter in the recirculation system will entrap particles larger than 10 micrometers. As a result, most of the free-floating particulate matter remaining after an experimental period will be collected. When the chamber gases have reached a desired level of cleanliness (as determined visually by the payload specialist) the recirculation system will be shut off, the chamber will be opened, and the exhaust-gas filter screen will be cleaned by the payload specialist using a hand-held, vacuum-operated cleaning tool. The filter in the recirculation system, however, is not meant to be cleaned during flight operations. It will be replaceable during ground servicing of the 0-GCF.

The recirculation system will be capable of moving 0.28 m^3/min (10 ft^3/min) of gaseous atmosphere. This will create an average gas velocity in the chamber volume of approximately 0.02 m/sec (0.05 ft/sec). When not being operated, the recirculation system can be valved from the chamber by the payload specialist. All hardware required for the system will be located outside the combustion chamber but inside the console.

Combustion-chamber instrumentation. - The chamber-wall and port-cover temperatures will be monitored during experiments by a minimum of six transducers - three for inner wall measurements and three for outer wall measurements. One external temperature measurement and one internal measurement will be selected as "representative" of their particular group, and their readouts will be visually displayed on the console control panel. The range of the transducers on the inner wall will be 256 to 422 K (0° to 300° F), and the range of those on the outer wall will be 256 to 339 K (0° to 150° F).

A temperature-sensing "rake" will be used inside the chamber to measure prevailing gas temperatures over the entire experimental testing period. The rake will have at least three transducers with a range of 256 to 589 K (0° to 600° F). The rake will be removable from the chamber for replacement (if needed) during flight. Further, the instrumentation rake will be designed so that it does not interfere with proposed hardware for the planned experiments, yet the design will still permit representative temperature measurements of the gas in the chamber to be made at any given time. The output of one transducer will be selected for visual monitoring and will be displayed on the console control panel.

At least two transducers will be used to indicate the pressure within the chamber. The range of each will be 0 to 31 N/cm^2 absolute (0 to 45 psia). The output of at least one of these transducers will be visually displayed on the console control panel at all times. A selector switch will enable the payload specialist to choose the transducer to be displayed.

A remote possibility exists, through accidental mismanagement of fuels or oxygen, that a combustible atmosphere could be created in the chamber, unknown to the payload specialist. For greater safety, a combustible-gas detector subsystem will be built into the 0-GCF to constantly monitor the contents of the chamber volume. The detector will be incorporated into the console. The output of the detector will be (1) visually displayed on the control panel, (2) tied into the caution and warning system of the Orbiter, and (3) recorded as a facility parameter during experiments. The detector will be a continuous-reading device and will have a range equal to 200 percent of the lower combustion limit of the fuels being used in any of the planned experiments.

<u>Chamber-atmosphere revitalization subsystem</u>. - A gas mixing and flow regulation subsystem will allow air (mixed from facility gaseous nitrogen and oxygen supplies) to be introduced into the chamber through a micrometer control valve during the active conduct of a combustion experiment. The system will have two solenoid valves (one teed off the facility gaseous nitrogen supply line and one teed off the gaseous oxygen supply line), two choked-flow orifices (one immediately downstream of each of the solenoid valves), a surge or mixing volume, a pressure switch that senses mixing volume pressure and either opens or closes both solenoid supply valves simultaneously, and a manually operated micrometer valve to regulate the flow of mixing volume contents into the combustion chamber. All hardware will be contained within the console.

The surge or mixing volume will help air to form by allowing incoming gaseous nitrogen and oxygen to mix effectively. The incoming gases will be metered through individual choked-flow orifices whose upstream supplies are regulated, in turn, by a pressure switch that senses the pressure of the mixing volume. The pressure switch will open the solenoid supply valves if the mixing-volume pressure is less than 27.5 N/cm^2 absolute (45 psia) and will close the valves if the pressure is 34.5 N/cm^2 absolute (50 psia) or greater. The micrometer valve will regulate the flow of manufactured air from the mixing volume into the combustion chamber. Maximum flow rate through this valve will be 0.05 kg/min (0.1 lb/min). It will have a minimum flow control range of 10:1. The micrometer valve will be as close as physically possible to the chamber and it will be mounted on the console control panel. The penetration into the chamber of the line from the micrometer valve, as well as any gas diffuser hardware inside the chamber (to enhance chamber-atmosphere gas mixing), will be considered a part of this subsystem.

Two types of instrumentation will be used in the revitalization subsystem to measure the mixing-volume pressure and temperature. The pressure sensor will have a range of 0 to 69 N/cm^2 absolute (0 to 100 psia); the temperature sensor will cover the range 256 to 322 K (0^o to 120^o F). The output of the selected transducers will be visible on the console front panel. There will be an electrical shutoff-switch permissive for the pressure switch to allow electrical deactivation of the pressure switch and hence to "safety" the two solenoid valves in the gaseous nitrogen and gaseous oxygen feedlines. This electrical switch will be mounted on the console control panel and will have indicator lights as an additional means of determining its disposition.

Gas and Liquid Supply Services and Bottle Storage

Detailed attention to inventory and control is the main impetus in the design of the gas and liquid services to the combustion chamber. The preliminary design is developed from the following facts:

(1) Each individual reactive gas will be metered, by means of a micrometer valve into either a previously evacuated chamber ($\leq$0.07 N/cm^2 absolute; 0.1 psia) or a previously evacuated test device.

(2) The nonreactive gases (e.g., helium and nitrogen) will either be metered into a previously evacuated chamber or introduced in bulk quantity, depending on the experiment and its operational phase.

(3) For those experiments using significant quantities of liquids (e.g., >0.5 cm^3 (0.03 in^3)), the liquids will be metered into the test device within the chamber when the chamber is at a pressure between 3.5 and 10.1 N/cm^2 absolute (5 and 14.7 psia).

Each gas or liquid will have its own storage container, transfer line, and valving for total or partial system evacuation, storage-tank loading, fluid transfer, pressure relief, and venting. All valving will be capable of sealing against vacuum.

Generalized flow subsystem. - The 0-GCF will have, as a minimum, storage and transfer hardware for a low-vapor-pressure liquid hydrocarbon and gaseous methane, nitrogen, oxygen, and helium. A number of the requirements for these subsystems are common and can be dealt with by describing a "generalized flow subsystem." Then, only the specific subsystem requirements and variations (relative to the general subsystem) for each separate fluid need be discussed.

Storage tank: The storage tank or tanks will be located outside the habitable volume of Spacelab, on the exterior surface of a pressure bulkhead or on a pallet. The storage-facility insulation system will be required to keep the tank contents, as well as all subsystem hardware outside the habitable volume, at 295 ±11 K (70° ±20° F). The storage tank will be loaded only from outside the Spacelab habitable volume. A safety relief valve will be incorporated into the fill connector on the tank to protect against possible overpressurization of the tank. The fill connector - relief valve does not have to be accessible after tank loading. Provisions will be made, for the reactive gases, to passively handle any gas vented from the tank because of overpressurization during both the prelaunch and postlanding periods when the Spacelab is installed in the Orbiter.

Fluid transfer line: A fluid transfer line, with flow-control hardware, will connect the storage facility with the combustion chamber. The penetration of

this line through the chamber wall, as well as any hose connector or diffuser inside the chamber (either to connect the line to experimental hardware or to enhance chamber-atmosphere gas mixing) will be considered part of the subsystem. The volume of the transfer line will be the minimum consistent with the fluid design flow rate. (Design flow rates are listed in the separate sections for each fluid.) The transfer line will contain at least four valves, or equivalent hardware, to provide the following services:

(1) Isolation of the storage tank: This shutoff feature will be as close as physically possible to the storage tank yet still be capable of being manually operated from inside the Spacelab habitable volume during orbital operations.

(2) Isolation of the combustion chamber and precise regulation of gas flow into the chamber: The manually operated micrometer valve will be as close as physically possible to the chamber and will be mounted on the console control panel.

(3) Venting of the transfer-line volume between the storage-tank isolation valve and the chamber micrometer isolation valve: The transfer-line vent will be located as close as physically possible to the storage-tank isolation valve. Its main purposes are to allow evacuation of the transfer-line volume before the line is charged with fluid and to allow a storage-tank slow dump, if necessary for any reason, thereby minimizing the quantity of fluid flowing through the combustion chamber and its vent subsystem.

(4) Transfer-line overpressure relief: A relief valve will parallel the manually operated transfer-line vent valve.

Instrumentation: A pressure-sensing transducer will be used to measure the transfer-line pressure between the storage-tank isolation valve and the chamber isolation valve. This measurement will be used to indicate that the line is indeed being evacuated during vacuum purging and, after the line has been charged with fluid, that a flow potential exists across the chamber micrometer isolation valve. Visual readout of this transducer, as well as all others required in each specific fluid subsystem, will be available on the console control panel.

[illegible]rlocks: There will be an interlock system between the transfer-line vent valve and each of the isolation valves (i.e., at the storage facility and at the chamber wall). However, overrides will be used to permit either the storage or chamber isolation valves to be intentionally opened while the transfer-line vent valve is open. These overrides will permit (1) a fluid dump without the flow entering the combustion-chamber volume, (2) an easier vacuum purge of the transfer line (i.e., simultaneously through both the transfer-line vent

valve and the chamber vent subassembly), and (3) a slow chamber-volume vent action, except for the gaseous nitrogen subsystem, if necessary for any reason.

Gaseous methane subsystem. - The gaseous methane subsystem (fig. 4) will incorporate the following specific requirements in addition to those of the generalized flow subsystem:

Storage tank: The storage tank will have an internal volume of approximately 0.014 cubic meter (0.5 ft^3). The operating pressure of the tank will be 20.7 N/cm^2 absolute (30 psia), which will initially allow a pressure budget of 10.3 N/cm^2 (15 psi) to be used for gaseous methane transfer from the tank to the combustion chamber.

Gas transfer line: The gas transfer line will only be large enough to permit a room-temperature (294 K; 70° F) gaseous methane flow rate of 9×10^{-4} kg/sec (2×10^{-3} lb/sec). At this flow rate, a gas-mixture-flammability tube experiment can be charged in 30 seconds.

Instrumentation: The range of the transfer-line pressure transducer will be 0 to 31 N/cm^2 absolute (0 to 45 psia). A second transducer will be used in this fluid subsystem to sense the transfer-line pressure inboard of the chamber isolation valve. This measurement will be used to charge the specific combustion experiment by a partial pressure technique. The transducer's range will be 0 to 0.7 N/cm^2 absolute (0 to 1 psia). It will be capable of being manually valved off from the transfer line to prevent inadvertent overranging during nonuse periods.

Interlocks: There will be an interlock system between the combustion-chamber pressure measurement and the valve that isolates the second pressure transducer in the transfer line (i.e., the transducer inboard of the chamber isolation valve). This interlock will be such that the transducer isolation valve can only be opened if the chamber pressure is 0.7 N/cm^2 absolute (1 psia) or less.

Liquid fuel subsystem. - The liquid fuel subsystem (fig. 5) will incorporate the following specific requirements in addition to those of the generalized flow subsystem:

Storage tank: The storage tank, as in the gaseous methane subsystem, will have an internal volume of approximately 0.014 cubic meter (0.5 ft^3). The operating pressure of the tank will be 45 N/cm^2 absolute (65 psia), which will allow a pressure budget of 34.5 N/cm^2 (50 psi) to be used for liquid-fuel transfer from the storage tank to the combustion chamber. The tank will contain a positive displacement device, such as a bellows or diaphragm, which will serve to segregate pressurizing gas from the stored liquid and which will provide a movable surface during periods of liquid expulsion.

Storage-tank pressurization system: The storage-tank pressurization system will use gaseous nitrogen from the combustion-facility supply. The pressurizing gas will be taken from the facility supply at a point downstream of the gaseous nitrogen storage isolation valve. The pressurizing system will provide a pressurizing potential adjustable up to 45 N/cm^2 absolute (65 psia).

Liquid transfer line: The liquid transfer line will only be large enough to permit a room-temperature (294 K; 70° F) liquid flow rate of approximately 6.5×10^{-6} m^3/sec (2×10^{-4} ft^3/sec). At this flow rate, a sufficient quantity of fuel for a typical liquid-pool combustion experiment can be transferred in 2 minutes.

Instrumentation: The range of the transfer-line pressure transducer will be 0 to 45 N/cm^2 absolute (0 to 65 psia). A second transducer will be used in this fluid subsystem to sense the transfer-line pressure upstream of the liquid-fuel storage isolation valve. This measurement will be used to indicate the liquid-fuel storage pressure (and hence that a flow potential exists across the storage isolation valve). The range of this transducer will also be 0 to 45 N/cm^2 absolute (0 to 65 psia).

Interlocks: No additions will be made to the interlocks of the generalized system.

Gaseous nitrogen subsystem. - The gaseous nitrogen subsystem (fig. 6) will incorporate the following specific requirements in addition to those of the generalized flow subsystem:

Storage-tank assembly: Use of approximately 38.6 kilograms (85 lb) of gaseous nitrogen is currently anticipated for experimental purposes in the 0-GCF. This quantity, carried as a gas, will require at least two pressurized containers. The containers can be identical to the standard nitrogen tanks presently considered as baseline equipment for the Orbiter. (Use of tanks of identical design will definitely cut costs.) The operating pressure of the two-tank storage system is expected to be between 1379 and 1724 N/cm^2 absolute (2000 and 2500 psia).

The gaseous nitrogen will be supplied into the transfer line within the habitable volume of Spacelab at a pressure of 148 N/cm^2 absolute (215 psia) or less. Hence, an additional requirement for the storage system will be at least one stage of pressure regulation, which will be located outside the habitable volume of Spacelab. The stage will be capable of passing a room-temperature gaseous nitrogen flow of 0.008 kg/sec (0.017 lb/sec) for use as deluge gas for the combustion-chamber volume. At this flow rate, the chamber can be charged with 1 atmosphere of gaseous nitrogen in 60 seconds. The pressure

regulation equipment presently considered baseline for the Orbiter could also be used for this application.

Gas transfer line: The gas transfer line will only be large enough to permit a room-temperature gaseous nitrogen flow of 0.008 kg/sec (0.017 lb/sec). The transfer line will have a tap-off "T" to supply gaseous nitrogen for pressurizing liquid-filled experiment tanks. This tap line, which will be capable of passing a flow rate of 6×10^{-6} m^3/sec (2×10^{-4} ft^3/sec), will run from the main transfer line to the liquid-fuel tank. It will contain a pressure regulation stage, a check valve, a manual shutoff valve, and a manual vent valve, all of which will be accessible from inside the habitable volume of Spacelab during orbital operations. The pressure regulation stage will have an adjustable downstream pressure capability of up to 45 N/cm^2 absolute (65 psia). It will also have a "closed" indicator light on the console control panel. The check valve will have a cracking pressure of 0.07 N/cm^2 differential (0.1 psid) and a reset pressure of 0.3 N/cm^2 differential (0.5 psid). The manual shutoff valve will serve as a permissive for pressurant gas flow and as a positive isolation between the liquid-fuel tank and the main gaseous nitrogen transfer line. This valve will have a "closed" indicator light on the console control panel.

Inside the console the transfer line will have a second tap-off "T," which will be referred to as a deluge flow line. This line will be capable of passing the 0.008-kg/sec (0.017-lb/sec) flow rate required of the transfer line. A normally closed solenoid valve, located immediately outside the combustion-chamber wall, will control deluge gas flow.

Instrumentation: The range of the transfer-line pressure transducer will be 0 to 172 N/cm^2 absolute (0 to 250 psia). This measurement will also be used to indicate that a flow potential exists across the regulation stage in the pressurization gas tap-off line.

Interlocks: An interlock system between the transfer-line vent valve and the solenoid valve in the chamber deluge line will prohibit opening of the solenoid valve if the vent valve is open. There will be a pressure-switch-controlled interlock between the facility chamber volume and the normally closed solenoid valve in the deluge line. This interlock will deactivate the deluge valve solenoid when pressure in the chamber is above 10.3 N/cm^2 absolute (15 psia).

Gaseous oxygen subsystem. - The gaseous oxygen subsystem (fig. 7) will incorporate the following specific requirements in addition to those of the generalized flow subsystem:

Storage-tank assembly: Use of approximately 13.6 kilograms (30 lb) of gaseous oxygen is currently anticipated for experimental purposes in the combustion facility. This quantity will be carried as a pressurized gas in a single

tank. The tank can be identical to the standard nitrogen tank presently considered as baseline equipment for the Orbiter. Operating pressure of the storage tank is expected to be between 1034 and 1379 N/cm^2 absolute (1500 and 2000 psia).

The gaseous oxygen will be supplied into the transfer line within the habitable volume of Spacelab at a pressure of 148 N/cm^2 absolute (215 psia) or less. Hence the requirement exists for at least one stage of pressure regulation. This equipment, located outside the habitable volume of Spacelab, will be capable of passing a room-temperature gaseous oxygen flow rate of 3.9×10^{-3} kg/sec (8.5×10^{-3} lb/sec). At this flow rate, the partial pressure of the oxygen required to form air in the combustion chamber can be established in 30 seconds The pressure regulation equipment presently considered baseline for the Orbiter could also be used for this application.

Gas transfer line: The gas transfer line will only be large enough to permit a room-temperature gaseous oxygen flow of 3.9×10^{-3} kg/sec (8.5×10^{-3} lb/sec).

Instrumentation: The range of the transfer-line pressure transducer will be 0 to 172 N/cm^2 absolute (0 to 250 psia). A second transducer will be used in this subsystem to sense the transfer-line pressure inboard of the chamber isolation valve. This measurement will be used to charge the combustion chamber by a partial pressure technique. The transducer's range will be 0 to 10.3 N/cm^2 absolute (0 to 15 psia). It will be capable of being manually valved off from the transfer line to prevent inadvertent overranging during nonuse periods.

Interlocks: There will be an interlock system between the combustion-chamber pressure sensor and the valve that isolates the transducer inboard of the chamber isolation valve. This interlock will be such that the transducer isolation valve can only be opened if the chamber pressure is 10.3 N/cm^2 absolute (15 psia) or less.

Gaseous helium subsystem. - The gaseous helium subsystem (fig. 8) will incorporate the following specific requirements in addition to those of the generalized flow subsystem:

Storage-tank assembly: Use of approximately 0.7 kilogram (1.5 lb) of gaseous helium is currently anticipated for experimental purposes in the combustion facility. This quantity will be carried as a pressurized gas in a single tank. As in the gaseous nitrogen and oxygen subsystems, the gaseous helium storage tank can be identical to the Orbiter standard nitrogen tank. Operating pressure will be approximately 689 N/cm^2 absolute (1000 psia).

The gaseous helium will be supplied into the transfer line within the Spacelab habitable volume at a pressure of 148 N/cm^2 absolute (215 psia) or less. Again, as with the gaseous nitrogen and oxygen subsystems, a pressure regulation stage

is required. Pressure regulation equipment presently considered baseline for the Orbiter can conceivably be used. It will be located outside the habitable volume of Spacelab and will be capable of passing a room-temperature gaseous helium flow rate of 5.4×10^{-4} kg/sec (1.2×10^{-3} lb/sec). At this flow rate the chamber can be charged with 1 atmosphere of gaseous helium in 2 minutes.

Gas transfer line: The gas transfer line will only be large enough to permit a flow of 5.4×10^{-4} kg/sec (1.2×10^{-3} lb/sec).

Instrumentation: The range of the transfer-line pressure transducer will be 0 to 172 N/cm^2 absolute (0 to 250 psia). A second transducer will be used in this fluid subsystem to sense the transfer-line pressure inboard of the chamber isolation valve. This measurement will be used to charge the chamber volume by a partial pressure technique. The transducer's range will be from 0 to 10.3 N/cm^2 absolute (0 to 15 psia). It will be capable of being manually valved off from the transfer line to prevent inadvertent overranging during nonuse periods.

Interlocks: There will be an interlock system between the combustion-chamber pressure sensor and the valve that isolates the transfer-line second pressure transducer (i.e., the transducer used during charging of the chamber with helium). This interlock will be such that the transducer isolation valve can only be opened if the chamber pressure is 3.4 N/cm^2 absolute (5 psia) or less.

<u>Cabin-air supply subsystem</u>. - Even though the combustion facility will have its own resources for air, it will also be able to backfill the chamber with Spacelab cabin air. All hardware required for the air supply subsystem will be located within the console. The air supply subsystem (fig. 9) will incorporate the following requirements:

Air inlet diffuser: The air inlet diffuser is the entrance port into which air, from within the console, will flow to backfill the combustion chamber. The diffuser will be located in the lower section of the console. A covering material of mesh will be used.

Gas transfer line: A gas transfer line, with flow control hardware, will run between the diffuser and the gas distribution hardware located inside the combustion chamber. Downstream of the inlet diffuser, the transfer line will contain a filter, a check valve, and a manual repressurization valve, in that order. The check valve will have a cracking pressure of 0.03 N/cm^2 differential (0.05 psid) and a reset pressure of 0.07 N/cm^2 differential (0.1 psid). The manual repressurization valve will be a micrometer type. It will be used for isolation of the chamber and for precise regulation of gas flow into the chamber. This valve will be as close as physically possible to the chamber wall. It will

be mounted on the console front panel and will have an "open-closed" indicator light displayed on the panel.

This flow subsystem should serve as a secondary means of repressurizing the combustion chamber in preparation for selected combustion experiments. It will also serve as a vernier control for elimination of any slight negative pressure within the chamber relative to the pressure within the Spacelab cabin. The design will size the subsystem components such that the chamber can be repressurized (from <0.07 to 10.1 N/cm^2 absolute (<0.1 to 14.7 psia)) in 2 minutes.

Instrumentation: No instrumentation is required for this subsystem.

Interlocks: There will be an interlock system between the manually operated repressurization valve and the combustion-chamber pressure sensor such that the valve cannot be opened if the chamber pressure is greater than 10.3 N/cm^2 absolute (>15 psia). In addition, there will be another interlock (electrical) that will prohibit any combustion experiments from being conducted in the chamber if the manual repressurization valve is open.

Combustion-Chamber Vent Assembly

The combustion chamber will have a vent assembly consisting of four separate subsystems that will serve as relief paths for excess pressure within the chamber. These subsystems will be known as

(1) The chamber-atmosphere vent

(2) The experiment-liquid vent

(3) The chamber backpressure control vent

(4) The chamber overpressure protection vent

Figure 10 is a schematic of the flow components and lines constituting the complete vent assembly. Specifications for each of these vent subsystems are detailed in the following paragraphs.

Chamber-atmosphere vent. - The chamber-atmosphere vent will see the most use during test operations. The vent, which will run between the combustion chamber and the ambient atmosphere outside the structural wall of the Orbiter, will be used to vent the chamber of combustion products after each experimental test. It will contain a flow control valve to be operated by the payload specialist at the console as well as an isolation valve located on the structural wall of the Spacelab habitable volume.

Vent line: A vent line, with flow control components, will connect the combustion chamber with ambient conditions outside the structural wall of the Orbiter. The chamber vent line will have two manually operated valves between

the combustion chamber and the structural wall of Spacelab. The valve immediately downstream of the chamber will be called the chamber-atmosphere vent valve (CAV); the second valve, located immediately inboard of the structural wall of Spacelab, will be called the vent permissive valve. The CAV valve will be located within the volume of the console that houses the combustion chamber. The CAV valve will be easily operated by a payload specialist standing directly in front of the console.

Besides removing the atmosphere from the chamber volume, controlled venting of the chamber will be a means of extinguishing any burning or smoldering particles that might remain after completion of selected experiments. To expedite particle extinguishment, the chamber vent system will be designed to attain a pressure level of 0.07 N/cm^2 absolute (0.1 psia), starting from 1 atmosphere, within 5 seconds. To aid in venting actions slower than 5 seconds or to safely expose the chamber volume to space for long periods of time, the CAV valve will be designed to be "indexed" at the 10- and 50-percent-open positions.

The following items, among others, will also be considered in the final design of the gas vent line:

(1) Minimizing the total weight of the line

(2) Minimizing the length of vent line "run" within the habitable segment of Spacelab

(3) Reducing the noise level associated with the chamber venting process

(4) Eliminating fire or explosion hazard in the vent line system by controlling the quantity of any unburned gases or flashed liquid

(5) Thermal lagging of the line to prevent the exterior surface temperature from rising above the allowable "touch temperature" of Spacelab.

Instrumentation: No instrumentation is required for this subsystem.

Interlocks: No interlocks are required for this subsystem.

Experiment-liquid vent. - The experiment-liquid vent will be used to vent contained pools of liquid fuel from within the combustion-chamber volume upon completion of experimentation. The vent flow rate will be variable and directly controlled by the payload specialist at the facility console. This vent line will also be capable of being isolated at the inboard side of the structural wall of Spacelab.

Liquid vent line: A liquid vent line, with flow control hardware, will connect the combustion-chamber volume with ambient conditions outside the structural wall of the Orbiter. The penetration of this line through the chamber wall, as well as a hose connector inside the chamber (to allow line connection to experimental hardware), will be considered part of the subsystem. The vent line will only be large enough to permit a flow of 2.3×10^{-5} m^3/sec (8×10^{-4} ft^3/sec)

of liquid fuel that will most probably flash within the vent line during outflow This venting will be accomplished through a nominal 6 9-N/cm^2 (10-psi) pressure differential By this venting action residual liquid from a typical liquid-pool combustion experiment can be removed from the chamber volume in 30 seconds

The vent line will contain a minimum of three valves, or equivalent hardware to provide the following services

(1) Isolation of the vent-line volume that is exterior to the habitable volume of Spacelab. This valve will be located immediately inside the structural wall of Spacelab and will be operated from inside Spacelab. This valve will be referred to as the "liquid vent permissive "

(2) Isolation of the chamber and fluid flow control during venting. This valve will be located within the volume of the console that houses the combustion chamber. Further, it will be such that it is easily operated by a payload specialist standing directly in front of the combustion chamber This valve will be referred to as the "liquid vent "

(3) Flow direction check This check valve will be located between the liquid vent valve and the exterior wall of the combustion chamber. It will have a cracking pressure of 0 03 N/cm^2 differential (0 05 psid) and a reset pressure of 0.07 N/cm^2 differential (0 1 psid) It will check flow directed into the chamber volume in order to prevent "blowback" of the vented fluid, which might develop because of possible liquid-fuel evaporation further downstream in the vent line

Instrumentation: One pressure-sensing transducer will be used in the vent-line plumbing. This transducer, which will sense the line pressure between the liquid vent valve and the liquid vent permissive valve, will range from 0 to 20.7 N/cm^2 absolute (0 to 30 psia). This measurement will be used to indicate that flow potential exists across the liquid vent valve Visual readout of this transducer will be available on the console control panel. Both the liquid vent valve and the liquid vent permissive valve will have "open-closed" indicator lights on the console control panel.

Interlocks: There will be an interlock system between the liquid vent valve and the liquid vent permissive valve. The liquid vent valve will not be operable unless the liquid vent permissive valve is already open

<u>Chamber backpressure control vent</u> - The chamber backpressure control vent subassembly will be used to automatically regulate vent gas flow from the chamber in such a way as to maintain a constant pressure in the chamber during experimentation that requires a continually renewable atmosphere The back-pressure level will be selected by the payload specialist.

Vent line: A vent line, with flow-control components, will connect the combustion chamber with the chamber-atmosphere vent line at a point inboard of the liquid vent permissive valve (see the discussion of the chamber-atmosphere vent line). The effective flow area of this subsystem will be such that it will vent a maximum of 7×10^{-3} m^3/sec (0.25 ft^3/sec) of room-temperature air through a 6.9-N/cm^2 (10-psi) pressure differential. At this flow rate, air equivalent to 1 chamber volume can be removed every 60 seconds. The vent line will have the smallest volume consistent with fulfilling this flow requirement.

The vent line will contain a minimum of two valves, or equivalent hardware, to provide the following services:

(1) Isolation of the chamber volume. This valve, which is a shutoff between the chamber volume and flow components further downstream in the vent system, will be referred to as the "backpressure control isolation valve." It will be located in the console and will be operated by a payload specialist standing in front of the console.

(2) Regulation of vent-gas flow from the chamber in such a way as to maintain a constant pressure in the chamber during that type of experimentation which requires a continually renewed atmosphere (e.g., smoldering combustion). This valve, which will be either pneumatically or mechanically operated, will be referred to as the "backpressure control valve." The valve operator will be capable of being manually preloaded to a pressure level that is proportional to the desired vent - no-vent operational threshold. If the pressure in the chamber becomes higher than the operational threshold, the valve will open proportional to the amount of gas that must be released to maintain threshold pressure in the chamber. If the chamber pressure is lower than the operational threshold, the valve will remain closed. If the operator of this valve is pneumatic, it will require an adjustable pressure-regulating device to control loading pressure. Supply gas to the regulator may be tapped from the gaseous nitrogen line (see the section Gaseous nitrogen subsystem). Another option is that the loader could be entirely mechanical and use a spring force to produce the desired operator load for the backpressure control valve. Whichever the case, however, the backpressure valve assembly will be such that steady-state pressure levels both above and below 1 atmosphere can be maintained in the chamber. The backpressure control valve will be able to handle minimum flow rates of 5.7×10^{-4} m^3/sec (0.02 ft^3/sec) of room-temperature air and still control pressure in the chamber to within ± 0.2 N/cm^2 absolute (± 0.3 psia). Both the backpressure control valve and its loader will be located in the console and will be easily operated by a payload specialist standing in front of the console.

Instrumentation: One pressure-sensing, or force-sensing, transducer will be used in conjunction with the loading device chosen for the backpressure control valve. Visual readout of this transducer will be available on the console control panel to enable the payload specialist to determine the amount of preload exerted on the backpressure control valve operator (and hence the steady-state pressure level to be maintained in the combustion chamber). The backpressure control isolation valve will have "open-closed" indicator lights on the console control panel.

Interlocks: There will be interlock systems between the vent permissive valve (see discussion of chamber-atmosphere vent) and the backpressure control isolation valve, as well as between the backpressure isolation valve and the backpressure control valve These interlocks will be such that the backpressure control valve cannot be opened unless both the vent permissive and the backpressure control isolation valves are open.

<u>Chamber overpressure protection vent</u>. - The chamber overpressure protection vent will be used as a safety relief line in the event the pressure in the combustion chamber inadvertently exceeds 20.7 N/cm^2 absolute (30 psia). The major flow component in this line will probable be a burst disk. During facility downtime this line will be capable of being isolated at the inboard side of the structural wall of Spacelab. The chamber overpressure protection subsystem will incorporate the following requirements:

Vent line: A vent line, with flow-control components, will connect the combustion chamber with ambient conditions outside the structural wall of the Orbiter. This vent line will parallel the chamber-atmosphere vent line. The purpose of the overpressure protection vent is to vent the combustion chamber from 20.7 N/cm^2 to 0.07 N/cm^2 absolute (30 to 0.1 psia) in 5 seconds or less.

The vent line will contain a minimum of two flow components, or equivalent hardware, to provide the following services:

(1) Isolation of the chamber from the vent line if the pressure in the chamber is less than 20.7 N/cm^2 absolute (30 psia), and full vent-flow capability if the pressure in the chamber is 20.7 N/cm^2 absolute (30 psia) or greater. This component will be a burst-disk assembly that will be blown open when a pressure of 20.7 N/cm^2 absolute (30 psia) or greater is generated in the chamber. The component will be located within the console. It will be mounted for convenient removal and replacement during ground servicing of the facility.

(2) Isolation of the vent-line volume exterior to the habitable volume of Spacelab. This valve will be located immediately inboard of the structural wall of Spacelab and will be operable from inside Spacelab. This valve will be referred to as the burst-disk permissive."

Instrumentation: One pressure-sensing transducer will be used in the vent-line plumbing. The transducer, which will sense the line pressure between the burst disk and the burst-disk permissive valve, will have a range of 0 to 20.7 N/cm^2 absolute (0 to 30 psia). This measurement will be used to indicate that flow potential exists across the burst disk. Visual readout of this transducer will be available on the console control panel. The burst-disk permissive valve will have "open-closed" indicator lights on the console control panel.

Interlocks: There will be an interlock system on the burst-disk permissive valve such that the combustion facility cannot be electrically powered unless the burst-disk permissive valve is open.

Facility Console, Subsystems, and Satellite Hardware

The combustion-facility console will be a modified Spacelab double rack and will house as a minimum the combustion chamber, the chamber fire-suppression system, the motion-picture cameras, and a helium-neon laser mounted on a movable optical bench. Besides the gas and liquid tank storage outside the Spacelab module, the console will be complemented by a center-aisle storage cabinet and a fluid-services "entrance panel" mounted on the interior surface of the Spacelab wall. The requirements for the console and its contents, as well as the other complementary equipment, are discussed in the following sections.

Facility console. - The requirements for the facility console are as follows:

Rack selection: Only certain Spacelab double racks can be used as the facility console because dedicated Spacelab subsystem components, presently baseline in some racks, preclude the addition of large experimental installations in those racks. At this writing three of the eight double racks in a Spacelab double module could house the combustion chamber, provided that an electrical distribution panel in the selected rack is considered movable. Two other racks could be used, provided that an electrical distribution panel and an intercom station in the selected rack are both considered movable. A considerable quantity of Spacelab baseline equipment completely precludes use of the remaining three double racks.

The combustion chamber will obviate use of the center support in any double rack selected to be the console. In addition, extra bracing or reinforcing of the proposed console will be necessary to insure structural integrity during exposure to all operating environments (see the section Environments).

Patchboard interchange. - As discussed earlier, electrical connections will be required between experimental hardware within the combustion chamber and electrical components in the console. It is anticipated that these electrical

components will deal with command, data management, caution and warning, and specialized services as required by individual experiments. The section Combustion Facility Chamber discusses only the method that will be used to get electrical communication from the experimental hardware through the chamber wall. This section discusses the method to be used from the chamber wall to a connect point in the volume of the console. A patchboard interchange will be used as part of the console control panel (fig. 11). This interchange will have routed to it, from the console interior, all necessary electrical services required by the entire spectrum of planned experiments. These service lines will terminate on a set of female pins that constitute one-half of a patching panel. Consider, now, the bulkhead fitting in the chamber wall. Either jumper cables or hard wiring will be run from the electrical bulkhead fittings in the chamber wall to the patchboard interchange subsystem. These wires will connect to a second set of female pins that constitute the second half of the proposed patching panel. The two half sets of female pins forming the patching panel will be connected by a manually changeable, programmable patchboard for each different experiment. This technique will require prewired patchboards for each experiment but will allow almost complete versatility in connecting any console-mounted electrical component, or other console-furnished electrical service, with experimental equipment in the combustion chamber. Also, a system will be used (technique and hardware included) that will allow verification of electrical continuity for all electrical connections made by means of this patchboard interchange subsystem. The verification system most probably will have several subparts, but it will be easily operated by a payload specialist during in-flight experiment setup.

Console-panel layout. - Throughout this facility description are listed hardware, switches, and readouts required on the console control panel for the various subsystems of the combustion facility. The console control-panel arrangement will group the controls, valves, readouts, etc., such that operations requirements for the various experiments, as well as for the facility itself, are easily satisfied by the payload specialist. The arrangement will also be as visual as possible relative to the flow paths of plumbing and electrical wiring comprising the facility.

Accelerometer package - Knowledge of any low-gravity accelerations imposed on the combustion facility during experimental periods is required. The experiments, at least during the actual burning or combustion periods, and in some cases during the deployment of the fuel to be burned, will require Orbiter accelerations to be held to 10^{-4} g or lower. Transients of even 10^{-2} g for over a tenth of a second could result in the movement of certain fuel samples within

the apparatus and, hence, in the loss of data. Therefore, the acceleration history present during experimental periods will be recorded by an accelerometer package incorporated into the console. This equipment will be capable of determining accelerations along the three major axes of the console The instrumentation will have a resolution of $\pm 5\times10^{-5}$ g and will cover the range from 1×10^{-5} to 5×10^{-3} g. The instrumentation package will contain the peripheral equipment needed to convert the transducer signals to electrical signals, to filter and amplify the signals, and finally to convert the conditioned signals to an analog output voltage that is linearly related to the acceleration being imposed on the facility. These signals will constitute part of the experimental data from the facility.

Chamber fire-suppression subsystem. - In most cases, chamber venting will suffice to extinguish any burning or smoldering particles remaining after completion of an experiment. However, in the event of an unexpected large-scale fire in the chamber, which might not be positively extinguished by a vacuum purge, the combustion facility will incorporate its own chamber fire-suppression subsystem. This subsystem is characterized by the following specific requirements.

Type of system: A system whose discharge will flood the combustion chamber will be used.

Extinguishing agent: Halon 1301, otherwise known as any of the following, will be used:

(1) Trifluorobromomethane

(2) Bromotrifluoromethane

(3) Bromotri or "BT"

(4) "Freon" FE 1301

Statepoints of agent: The Halon 1301 will be stored as a pressurized liquid and will be discharged as a gas

Number of storage bottles: Three separate storage bottles, and appropriate valving, will be employed (the same type of bottles that are now considered dedicated Spacelab hardware will be used).

Location of storage bottles: The bottles will be located within the Spacelab console housing the combustion-facility chamber. They will be mounted in the bottom rear of the console. Each assembly will be accessible for convenient removal and replacement and will not have quick-disconnect brackets.

System design goal: The goal will be to achieve a 6-percent concentration (by volume) of Halon 1301 within the combustion-facility chamber.

Distribution: The distribution system will achieve a 6-percent concentration (by volume) of Halon 1301 within a total flooding time of 4 seconds. Total

flooding time is the time that may pass from activation of a "fire" switch until the instant when the 6-percent volume mean concentration of Halon 1301 is achieved. Further, there will be a minimum soak time of 3 minutes after the desired concentration has been attained.

Halon 1301 flow control: Three separate supply bottles and valving will be used. Only one set of each will be used at a time. Halon 1301 flow will initially be activated by a squib valve. One valve will be required for each Halon 1301 storage bottle. Each storage bottle will be isolated from the combustion-facility chamber by means of a manual valve.

Activation: The fire-suppression system will be activated manually from an execution panel on the front face of the console that houses the combustion-facility chamber.

Switches and verification: The fire-suppression circuitry will have a "safe-arm" switch to prevent inadvertent operation and three "fire" switches as separate entities. An indicator light in the "safe-arm" circuit will denote the "arm" position. An indicator light in each of the "fire" circuits will denote open squib valves.

Electronic or electrically operated components: The electronic or electrically operated components will be such that they can be interrogated to determine whether or not they are in an operating condition.

Power source: The fire-suppression circuitry will be powered from either a battery contained within the console or the Spacelab emergency power distribution system. A switch will be provided for selection of the power source.

Pressure increase in facility chamber: The total increase in pressure of the sealed combustion chamber, due to introduction of one storage bottle of Halon 1301, will be less than 6.9 N/cm^2 gage (10 psig).

Motion-picture-camera installation. - Motion-picture recordings will be made of all planned combustion runs. The camera subsystem will use 16-millimeter color film and will be powered by electrical energy available from Spacelab. The subsystem will include three identical motion-picture cameras with nominal 122-meter (400-ft) film magazines and their mounts, controls, and instrumentation, as well as any facility and camera hardware that will give film magazine quick-change capability. All mechanical, electronic, and optical parts of this facility subsystem will be outside the combustion chamber. All equipment, except one camera and its mount, will be within the console.

Two of the cameras will be mounted inside the console and will view experiments through the upper and lower optical ports of the combustion chamber. Because of film-frame dimensions and magazine-changing considerations these two cameras will be mounted on their sides, with the film magazines

facing upward and their lens systems interfacing with the optical ports of the chamber. The mounting system for the cameras will allow remote, in-flight position adjustment of the cameras so that their lens systems view a vertical field inside the chamber. These cameras will be equipped with borescopes so that the payload specialist, standing in front of the console, can subjectively verify the field of view before, or at any time during, an experimental period (i.e., continuous reflex-viewing option) These cameras will also have the following capabilities: (1) remotely adjustable shutter, (2) remotely adjustable exposure control, (3) timing and time interlock, (4) remote film-speed adjustment, (5) remote film-footage counter, (6) lens changing, and (7) startup and shutdown of one or both cameras either automatically as part of an experimental sequence, or manually. All capabilities denoted as remote will be controllable from the console control panel. The magazines for these two cameras will be manually changed frequently, as often as between each experimental run. Therefore, access to the magazines on the cameras is mandatory. This access will be by hinged doors in the console control panel. The cameras themselves are not intended to be removable during flight, only during ground servicing of the facility.

The third camera will be a portable unit (brought out of storage only during periods of in-flight operation) and will have the capability of being mounted so that it can view experiments through the center service port of the combustion chamber The mounting of this camera will be hinged or cantilevered from either the facility-console frame or a special bracket integral with the combustion-chamber wall. The mounting will allow the camera to be swung away from the service port during installation and removal of experimental hardware or simply to give the payload specialist a direct view of the combustion-chamber contents The mounting system for the camera will allow in-flight position adjustment so that the camera lens system views a vertical field inside the chamber. The camera will be equipped with a borescope for field-of-view adjustment. This third camera will have the following capabilities: (1) adjustable shutter, (2) adjustable exposure control, (3) timing and time interlock, (4) remote film-speed adjustment, (5) remote film-footage counter, (6) lens changing, and (7) startup and shutdown (together with or separately from the other two cameras) either automatically, as part of an experimental sequence, or manually. All capabilities denoted as remote will be controllable from the same area of the console control panel as the other two cameras.

Helium-neon laser and optical bench. - This facility subsystem will enable laser Doppler velocimetry measurements to be taken during active conduct of combustion experiments. The subsystem will have two channels and will use a

differential Doppler mode or forward-scattered light. Each channel will be frequency shifted so that measurements obtained from the subsystem will have directional resolution. The subsystem will use either a four-beam polarization method (i.e., where the channels are separated by polarization techniques) or a three-beam method (i.e., where the channels are separated by virtue of a frequency shift in two of the beams). The subsystem will be capable of measuring velocities as low as 0.1 cm/sec (0.04 in/sec) and as high as about 200 cm/sec (80 in/sec).

The subsystem will include, but not be limited to, a helium-neon laser and its exciter; beam-splitting and flow direction adapter complete with electronic supply units; receiver optics; photomultiplier tubes with power supply and signal-processing equipment; beam deflection mirrors; an adjustable optical bench; controls; and instrumentation. All mechanical, electronic, and optical parts of this facility subsystem will be located outside the combustion chamber but inside the console.

Laser and exciter: The laser will be a helium-neon gas unit whose visible beam has a wavelength of 0.6328 micrometer. The beam power will be adjustable to 25 milliwatts. The exciter will be designed to provide the laser with sufficient starting potential, as well as current and voltage during steady-state operation. The unit will operate at 115 volts and 400 hertz and will draw no more than 200 volt-amperes of power.

Beam splitter, flow direction adapter, and electronic supply: These pieces of equipment will split the incoming laser beam into component beams, create frequency shifts between the components, and focus the components at a desired point of measurement within the chamber. The focusing point of the component beams (i.e., point of measurement) will be adjustable by ±3.8 centimeters (±1.5 in.) on either side of the vertical centerline of the combustion chamber (i.e., either side along the axes of the component beams). The resolution of this movement will be ±0.03 centimeter (±0.01 in.). The angle between the incoming component beams to the point of measurement will not change during this movement. These adjustments will be made by the payload specialist standing in front of the console.

Receiver optics, photomultiplier tube, and electronics: These pieces of equipment will collect Doppler-shifted light from the measurement point, convert the light information to an electrical signal, filter and amplify the signal, validate that the signal received is indeed a Doppler signal, and finally yield conditioned outputs in both digital and analog form. The digital output will be compatible with the Spacelab remote acquisition unit for data collection purposes. The analog signal will be compatible with the Spacelab data display system so

that a visual display of velocity versus time, for the combustion interval, is available to allow the payload specialist to immediately evaluate the test run.

When the point of measurement is moved by the payload specialist, the receiving lens will also move in tandem so that refocusing of the Doppler light on the aperture of the receiving apparatus is obviated. This tandem movement can be accomplished by an extra dimension of travel of the optical bench. The receiving aperture for the focused Doppler light will be adjustable by the payload specialist for proper optical alinement. A laser-line optical filter will be included ahead of any photomultiplier tube (or tubes) in the Doppler light-receiving package so that the incoming light will be attenuated to the wavelength band expected of the flame under study.

Laser-beam deflection mirrors: Any reflectors used to help direct the laser beam along a desired path within the console will be first-surface mirrors. In addition, the reflective surface will be overcoated with an antioxidant sealant to prevent degradation of its optical properties. The mirrors will have a flatness specification of $\lambda/10$. The mirror mounts will be adjustable for attaining and readjusting the laser-beam path.

Optical bench: The optical bench will be "U"-shaped. It will lie in a horizontal plane and surround the chamber such that the open side of the U faces the front of the console. Hence, the bench will encircle the sides and back of the combustion chamber. The back section of the bench will serve as a mounting surface for the laser, and the two legs of the U will serve as mounting surfaces for the beam splitter and the measurement-sensing equipment, respectively. The bench will have a rectangular box-beam cross section.

A rigidized structure is required, but not an immovable one. The bench will move in at least two dimensions: The bench will be capable of translating, within its mounting plane, in a front-to-rear direction inside the console. The amount of this movement will be ±5 centimeters (±2 in.) relative to the vertical centerline of the optical ports on either side of the chamber. The bench will also be capable of changing horizontal planes (i.e., translating vertically) inside the console. The amount of this movement will be ±5 centimeters (±2 in.) relative to the horizontal centerlines of the optical ports. So that the Doppler light-receiving apparatus will move in tandem with the beam splitter and flow-sensing equipment, there will be allowance for "left-right" translation of the bench. The amount of this movement will be ±3.8 centimeters (±1.5 in.). The resolution of any of these movement capabilities will be ±0.03 centimeter (±0.01 in.) Each type of movement will be independently controllable by the payload specialist standing in front of the console. The bench will be moved either mechanically or electromechanically.

Controls: A section of the console control panel will be used for the electrical switching, electrical controls, and bench movement controls required for the laser Doppler velocimeter subsystem. These controls will be grouped for ease of use by the payload specialist standing in front of the console.

Center-aisle storage cabinet. - Only the hardware required for a single experiment will be in the combustion chamber at any given time. Therefore, the basic equipment of other experiments, as well as any renewable supplies, must be stored. A center-aisle double cabinet will be used for this purpose.

Fluid-service "entrance panel". - A significant number of manual valves, pressure regulators, and readouts are required for gas and liquid supply services in order to isolate them from the storage facilities outside the habitable section of Spacelab and to control flow. Immediately inside the wall of the Spacelab each subsystem requires some sort of flow-control hardware, and in most cases instrumentation, to determine the flow potential or level of storage. This flow-control hardware and instrumentation will be mounted on a single "entrance panel" on the interior surface of the Spacelab wall (e.g., the end cone), conveniently grouped so that operations requirements are easily satisfied by the payload specialist. The panel front will be a visual representation of the plumbing flow paths.

Control and Data Subsystem

The control and data subsystem consists of the equipment and software for analyzing, conditioning, formatting, recording, transmitting, displaying, and storing the data and instructions for controlling and monitoring the combustion facility. The present intent is to telemeter complete information to the Mission Control Center from the facility and its experiments for as long as possible. When the Orbiter is out of direct communication with Mission Control, the facility and experimental data will be recorded and held within the constraints of Spacelab avionics equipment until communication between Orbiter and ground is reestablished.

For each experiment, certain group of steps, perhaps entire sequences, will be automated and ultimately controlled by some of the equipment baselined in the Spacelab command and data management subsystem. A control program (within the constraints of the Spacelab command and data management subsystem) will visually delineate the steps to be taken by the payload specialist in activating the facility, conducting the experiments, and deactivating the facility. The program will also be used to assure that a "safe" condition exists immediately before any given experimental combustion period. The program will verify, from transducer measurements, event devices, etc., that the proper

steps have been taken during any given operation. In the event of an anomaly, the program will be capable of indicating the area of the flow system where the trouble exists. A program override capability will allow the payload specialist to proceed, within his discretion, in the event of unforeseen failure of some permissive device or electronic component whose signal is used by the program.

The control and data subsystem will include and/or provide the following:

(1) Real-time visual readout of those parameters required for various other subsystems

(2) Recording of all events pertinent to the operation of the combustion facility (e.g., valve operation, ignitor current flow, camera actuation, and chamber illumination "on")

(3) Data-handling capability that will be through, as well as electrically compatible with, the Spacelab remote acquisition units and the high-rate multiplexer

(4) Measurement amplifiers (as required); supporting electronics; and other instruments in the form of temperature gages, pressure gages, gas sensors, etc., located to provide the desired information

(5) The capability to provide data to the Spacelab caution and warning system, which is critical to the safety of the Orbiter/Spacelab flight personnel.

Several instrumentation measurements in the telemetered data will be specified, for each experiment, so that the principal investigator can immediately determine the acceptability of each experimental run. These specified measurements will be available to him at the Mission Control Center.

Software will be available for a preflight checkout of the Spacelab - combustion-facility interface and the combustion facility itself. This software will consist of a series of routines and subroutines for use on the Spacelab experiment computer, which will communicate with the facility through the remote acquisition unit interface. Basic diagnostic routines will be incorporated. The software will also be used to perform simulated flight functional checkout immediately after the facility hardware is installed within Spacelab as well as during the Kennedy Space Center integration checkout. The simulated-flight program will consist of a series of routines and subroutines dedicated to ground operations of the combustion facility and its interfaces in a simulated flight manner. The functions of preflight, checkout flight, and simulated flight may be incorporated into a single software package if it is more technically effective.

Housekeeping Specifications

Hand-held vacuum cleaner. - As stated in the section Chamber-atmosphere recirculation system, an exhaust-gas filter screen will be installed in the upper elliptical head end of the chamber. This screen will be a mechanical trap for undesirable combustion products 100 micrometers or more in diameter and will effectively hold the particles until they can be removed by the payload specialist. It is presently intended that these particles be removed by means of a small hand-held vacuum cleaner inserted by the payload specialist into the chamber through a service port. This cleaning technique will minimize the requirements imposed on the Spacelab resources (e.g., extra vent lines and electrical power).

Surface contamination prevention. - Solid particles from combustion, as well as some inert particles used in tracer functions during the experiments, will definitely be present within the combustion chamber at the end of a test. These undesirable particles might jeopardize taking further photographic or laser Doppler velocimetry data by plating out on the surfaces of the optical ports. Several techniques will be available to prevent this contamination (e.g., anti-static coatings on the ports, mechanically covering the interior surface of a port with a replaceable transparent covering, or simply wiping the surfaces clean). These techniques will be readily handled by the payload specialist during orbital flight with minimal demands on the Spacelab resources. The result of the purging action will be verifiable by the payload specialist.

Postflight cleaning of chamber. - The technique and hardware to clean the inside of the combustion chamber after inflight testing will be available as a ground service function, not to be conducted during orbital flight. The cleaning plan will include a detailed self-explanatory procedure and will deal with the chamber volume inclusive of the first line of isolation valving. Also included will be a description of all necessary equipment removals or breakdowns required. The overall design of the combustion facility will enhance the execution of this cleaning process.

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Environments

Operational. - During ground operations, including handling and transportation, the 0-GCF will withstand the natural-environment design criteria specified in references 1 and 2. It will also withstand the induced-environment design criteria specified in references 2 and 3. Loads induced during transportation and handling will not impose a flight performance penalty.

During flight operations the 0-GCF will withstand the natural-environment design criteria specified in reference 2 for module and pallet equipment. It will

also be able to withstand induced environments in excess of those specified in reference 2 for module and pallet equipment. Operation of the 0-GCF will not result in induced environments in excess of those specified in reference 2.

Transportation. - The 0-GCF console will be shipped in a Government-furnished console handling-and-transport kit. Packaging for shipping facility equipment other than the console will be independently manufactured. The 0-GCF will be transported without degrading performance, service life, or reliability. Humidity, shock, temperature, pressure, and vibration will be controlled to levels less than those specified in references 1 to 3, as appropriate, and will not dictate 0-GCF design. The 0-GCF will have provisions for attaching handling fixtures to permit horizontal and vertical installation and removal operations. The console transportation container, as well as the containers for other facility equipment, will be instrumented to verify that the limits of references 1 to 3 have not been exceeded.

Storage. - The 0-GCF console, and all facility equipment, will be capable of being stored horizontally or vertically for extended times. When storage is required, the constituents of the 0-GCF will be protected and properly conditioned to assure that their mission capability is not adversely affected. The 0-GCF will require no routine maintenance during storage.

INTERFACE AGREEMENTS

The Shuttle Payload Integration and Development Program Office at Johnson Spacecraft Center requires a payload integration plan to be submitted for every complete payload to be flown in the Orbiter. This document will be compiled by the mission manager in charge of the payload of which the 0-GCF is a part. So far these mission managers have been from the Marshall Space Flight Center. The mission manager, in turn, will require an experiment requirements document for each of the facilities and/or experiments making up the total payload. These documents will be compiled in turn by the project engineer, for a facility, and by the principal investigator, for an individual experiment.

For a facility (e.g., the 0-GCF) the project engineer will require experiment interface agreements with individual principal investigators whose experiments will be conducted as part of the facility program. The purposes of an experiment interface agreement are (1) to obtain investigator agreement with all experiment interface design requirements and resource allocations, and (2) to specify and control the interface between the experiment and the Spacelab/Orbiter and, as applicable, between the experiment and the total payload. Data required for the preparation of the experiment interface agreements will be provided by the individual principal investigators.

CONCLUDING REMARKS

The advent of the Space Transportation System (STS) Orbiter and its Spacelab payload definitely enhances the future of "zero gravity" combustion experimentation. The greatly increased length of test time available, as well as the allowance for direct participation of a scientist in the experiment, are two major improvements over previous ground-, aircraft-, and sounding-rocket-based experimentation.

A 1974 overview study by NASA to determine those combustion areas having a strong scientific basis for research in the low gravity of space yielded a list of experiments ranging from rapid burning to long-term smoldering. These experiments have been used to form a baseline for the design of a combustion facility for Spacelab.

The zero-gravity combustion facility preliminary design proposed herein will permit an experimenter (1) to use suitable contained liquid, gas, or solid fuels; (2) to specify and establish the composition and pressure level of the atmosphere in which the combustion will take place; (3) to characterize the experiment with common types of instrumentation as well as selected specialized equipment; and (4) to study the combustion process visually by direct observation and by motion-picture coverage and to obtain time histories of pertinent experimental parameters.

During an experimental period, the facility will depend on the Spacelab resources for power, heat rejection, vacuum, and data management and communications. Activating the facility and preparing it for the various experiments, performing the experiments, and shutting down the facility will be largely manual operations performed by flight personnel. This intense manual participation in the research activities will contribute flexibility and versatility to the operations as well as provide the desired direct subjective participation in the experimentation.

Use of the proposed facility will be open to the entire scientific community. The investigators and their experiments for Spacelab missions with the proposed combustion facility will most probably be selected through an Announcement of Opportunity issued by NASA.

REFERENCES

1. Space Shuttle System Payload Accommodations; Level II, Program Definition and Requirements, Vol. XIV, JSC 07700, Rev. E, NASA Lyndon B. Johnson Space Center, June 17, 1977. (Available from NASA Johnson Space Center, Management Systems Office, Code LV, Houston, Tex. 77058.)

2. Spacelab Payload Accommodation Handbook, SLP 2104, Issue 1, Rev. 0, European Space Agency for NASA George C. Marshall Space Flight Center, 30 June 1977. (Available from NASA Marshall Space Flight Center, Documentation Control Repository, Marshall Space Flight Center, Ala. 35812.)

3. Launch Site Accommodations Handbook for STS Payloads, K-STSM-14.1, Rev. 3, NASA Kennedy Space Center, June 1976. (Available from NASA Kennedy Space Center, NWSI Documents Dept., Code NWSI-D, Kennedy Space Center, Fla. 32899.)

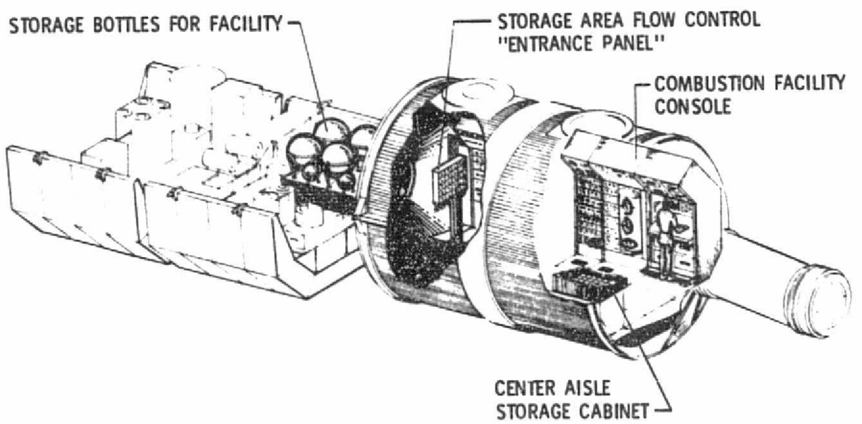

Figure 1. - Artist's concept of Spacelab zero-gravity combustion facility (0-GCF).

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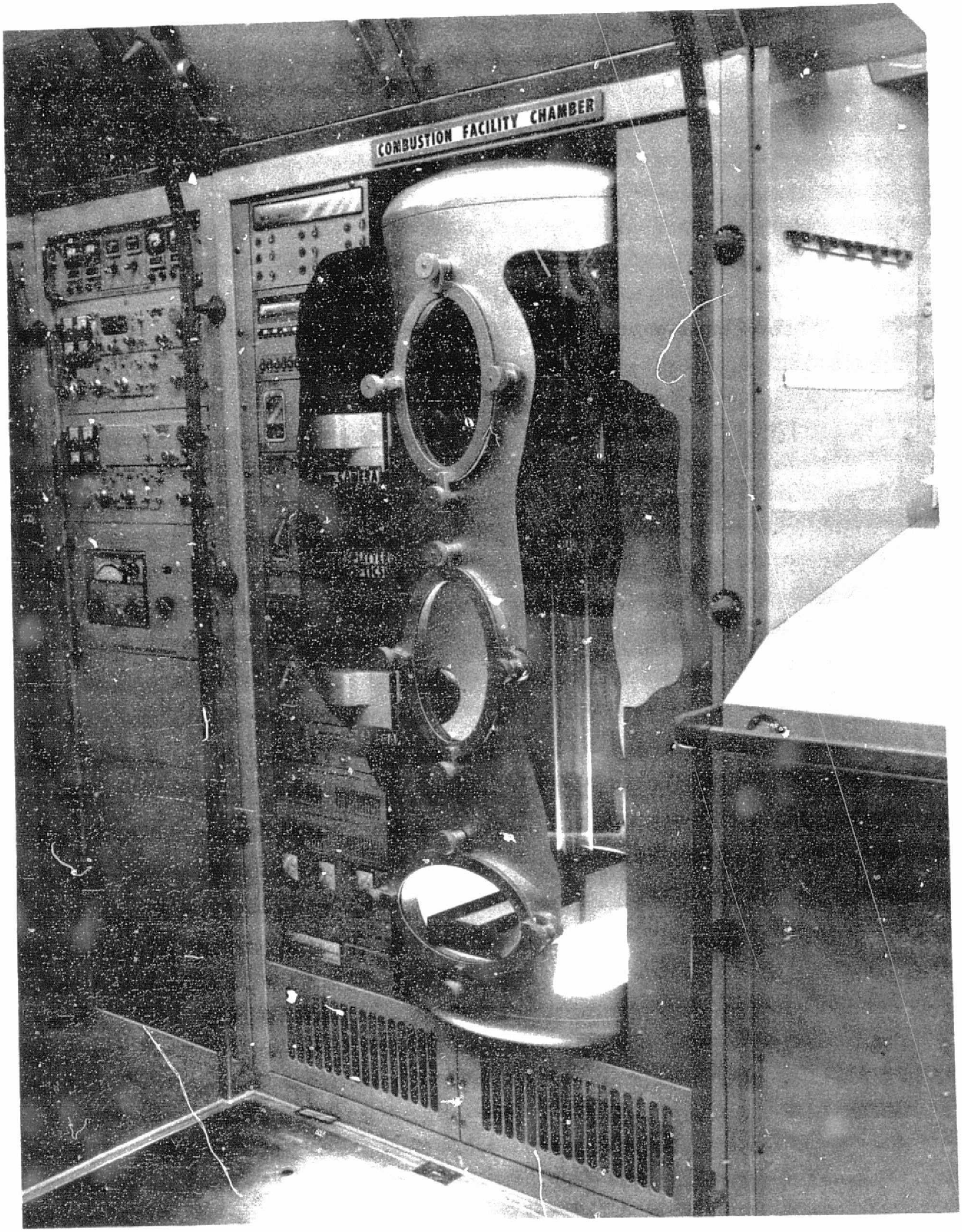

Figure 2. - Combustion-facility chamber in Spacelab console.

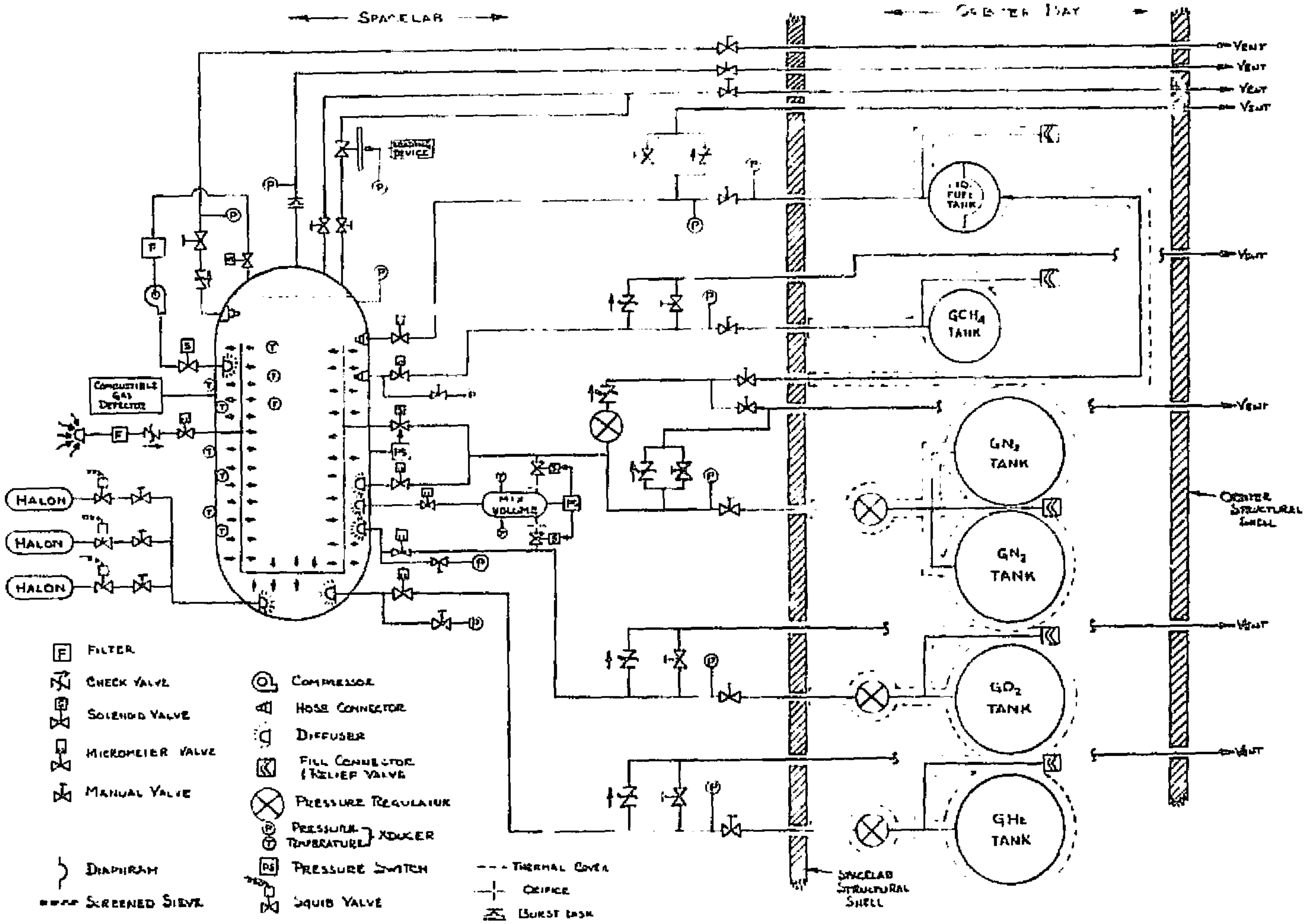

Figure 3. - Schematic of combustion-facility plumbing.

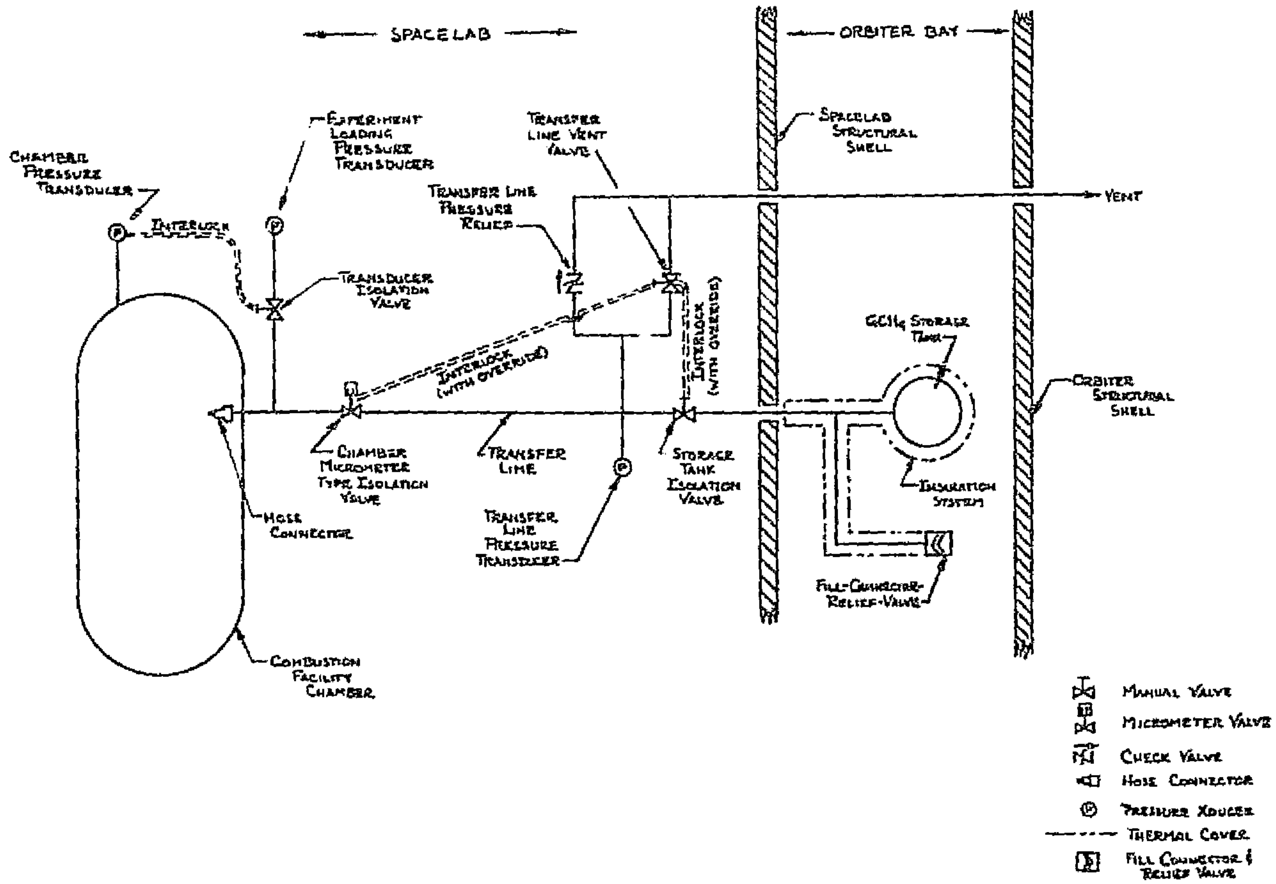

Figure 4 - Schematic of gaseous methane storage and supply subsystem.

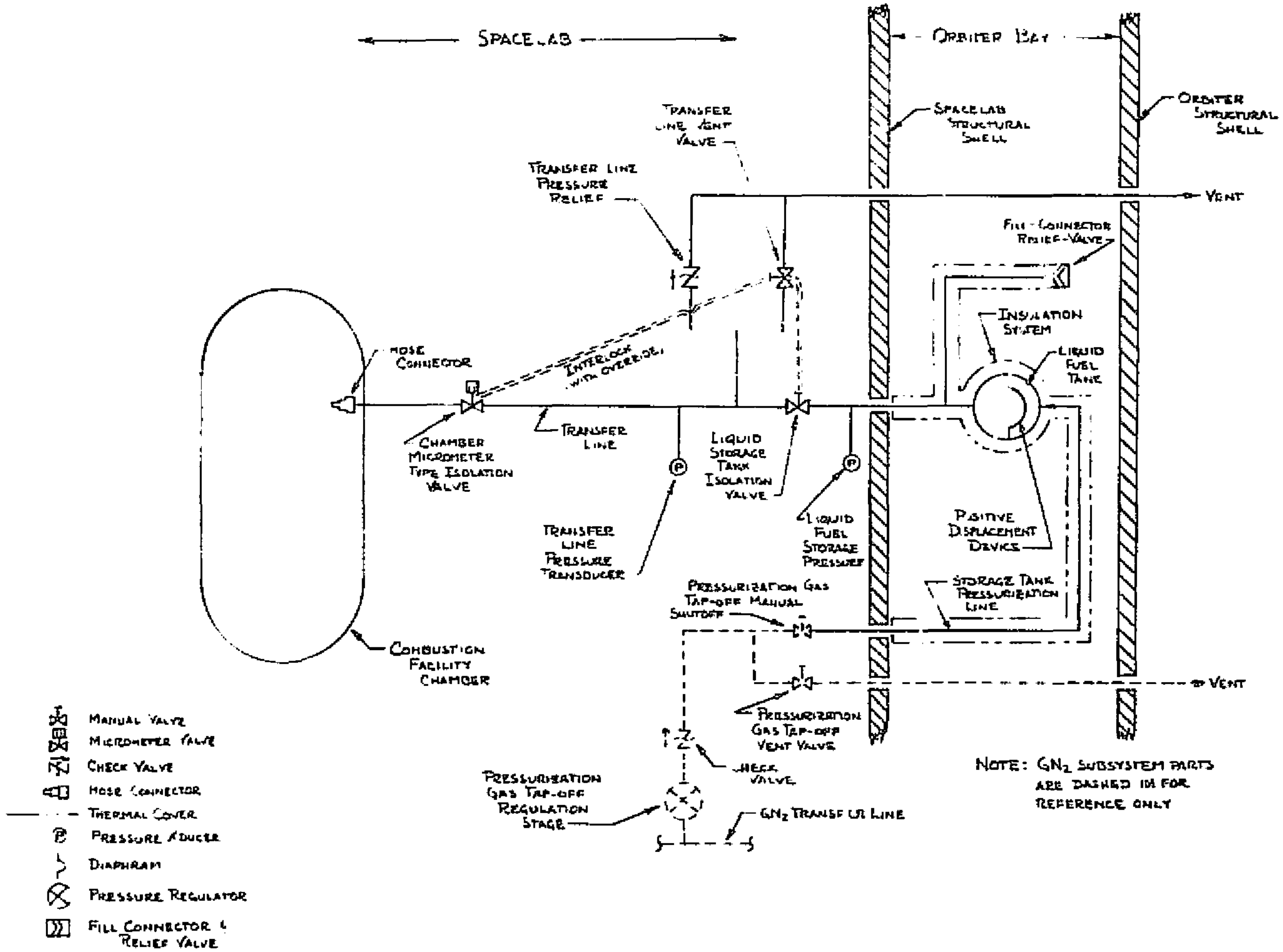

Figure 5. - Schematic of liquid-fuel storage and supply subsystem.

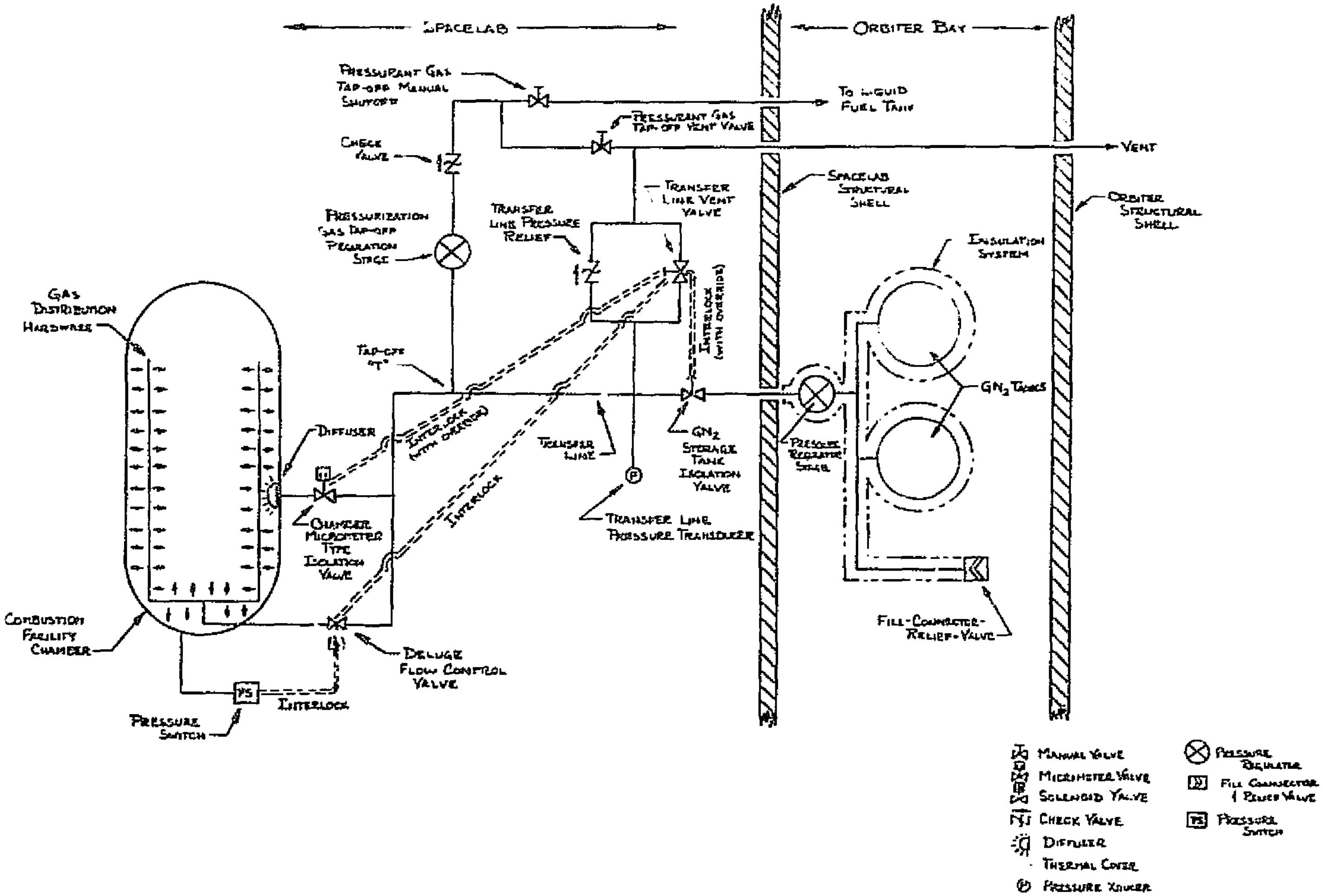

Figure 6. - Schematic of gaseous nitrogen storage and supply subsystem.

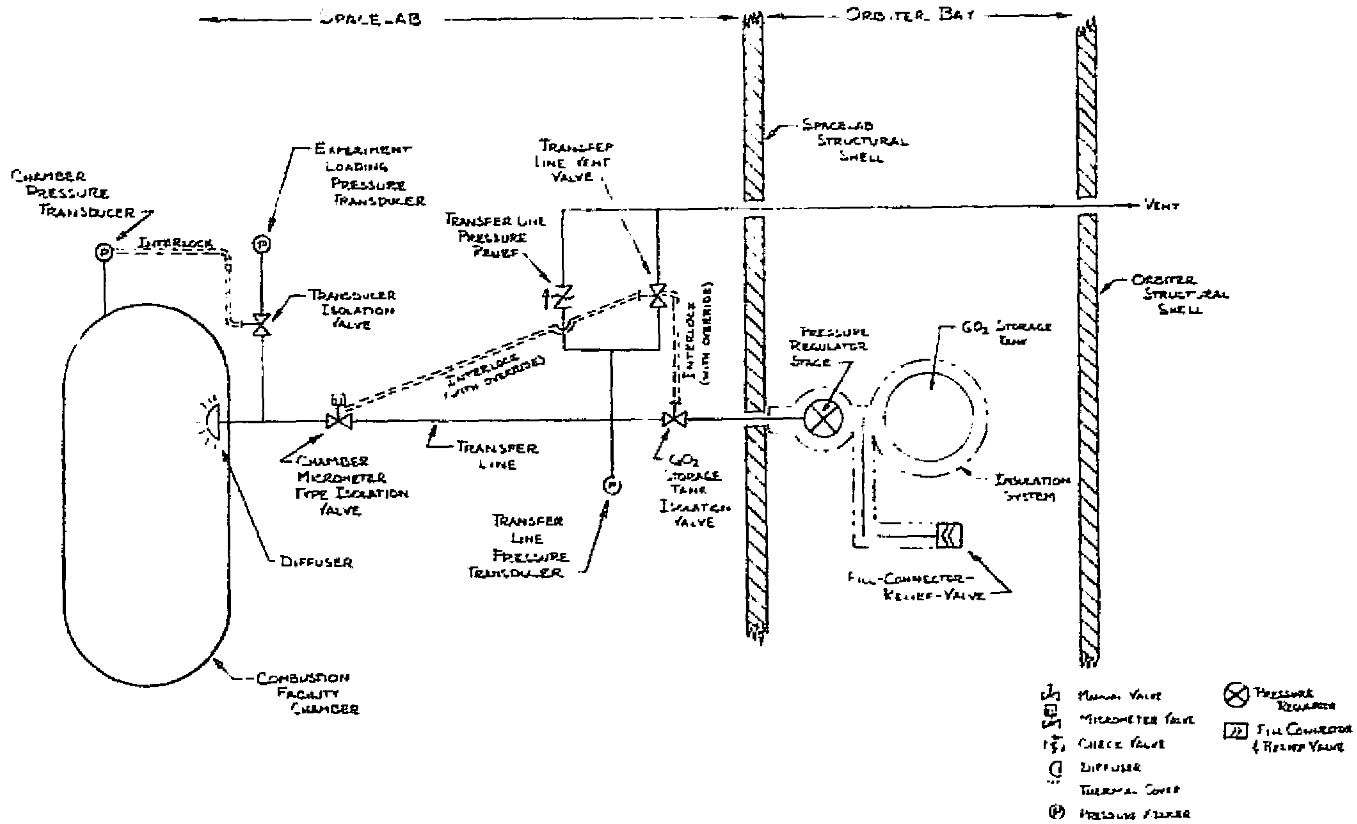

Figure 7. - Schematic of gaseous oxygen storage and supply subsystem.

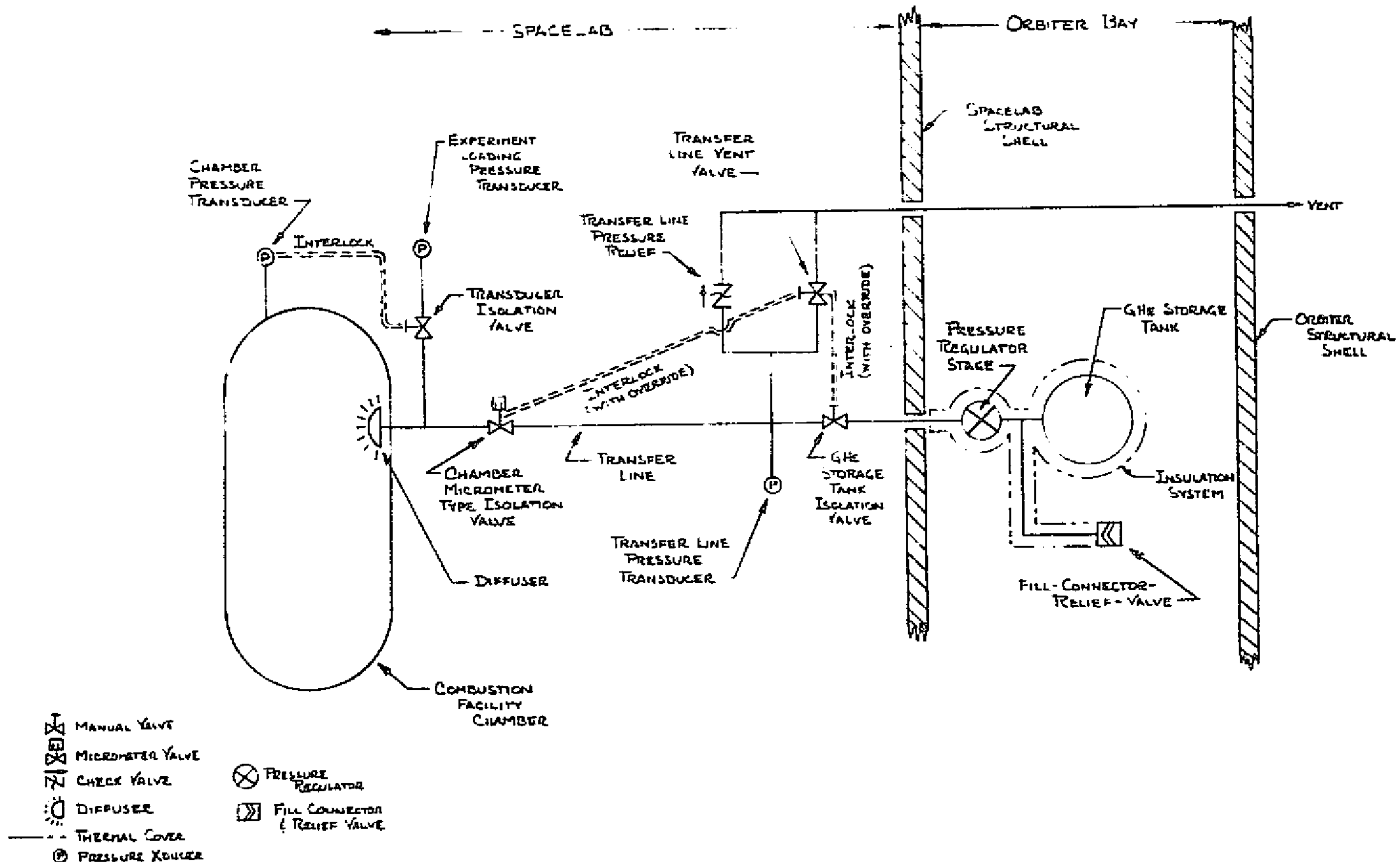

Figure 8. - Schematic of gaseous helium storage and supply subsystem.

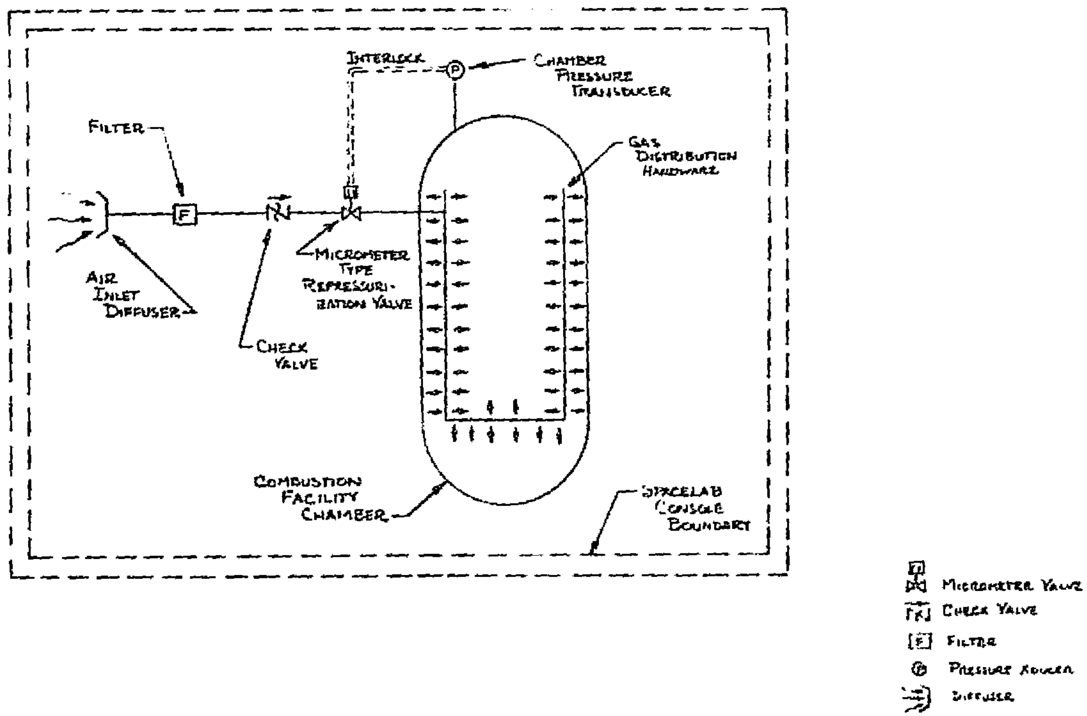

Figure 9. - Schematic of supply subsystem for air from Spacelab cabin.

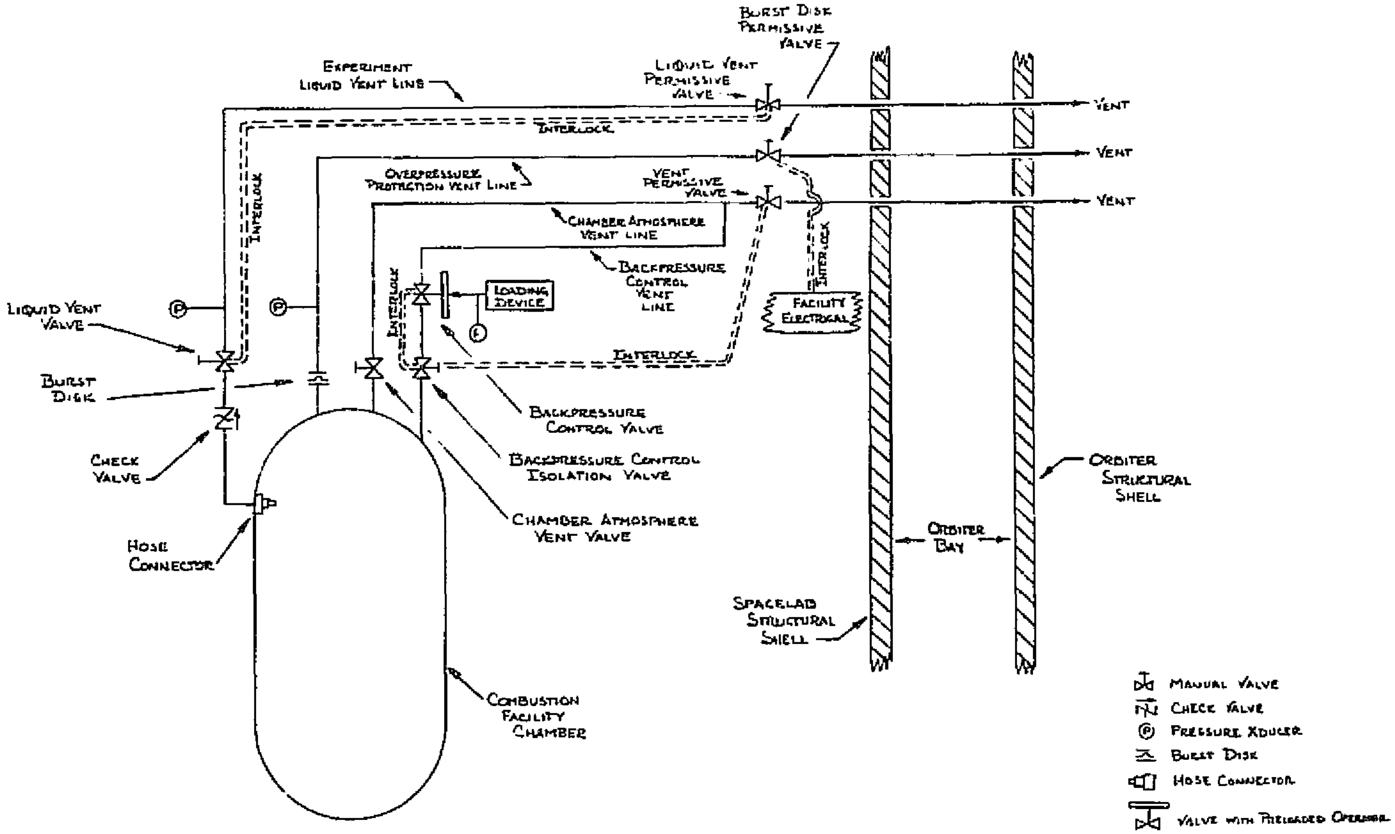

Figure 10. - Schematic of complete vent assembly.

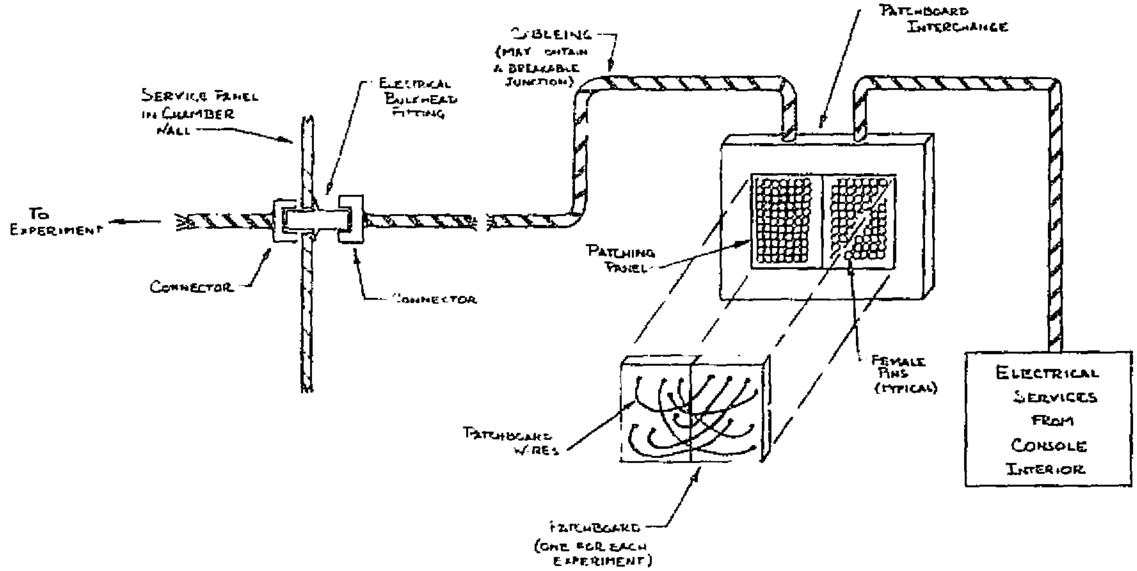

Figure 11. - Schematic of proposed patchboard interchange subsystem.